A Visit to Transurania

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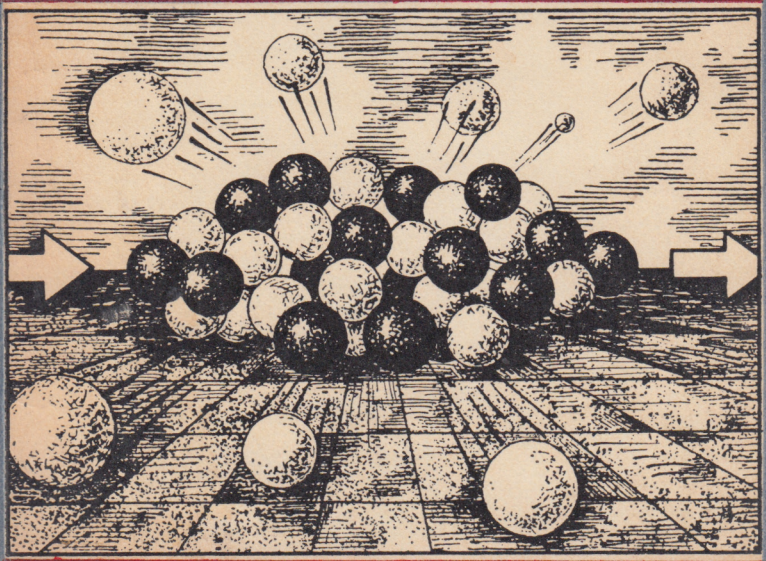

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ИЗДАТЕЛЬСТВО
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ПУТЕШЕСТВИЕ В МИР ТРАНСУРАНОВ

A Visit to Transurania

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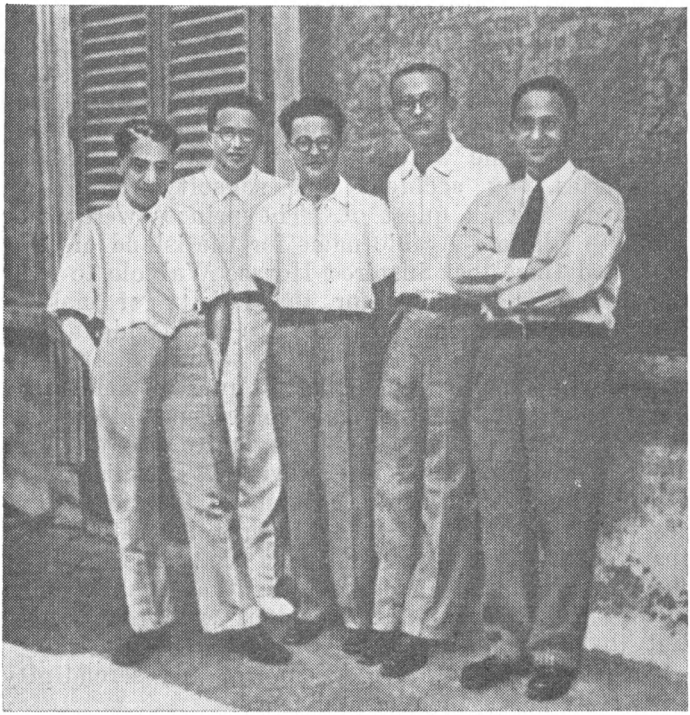
CONTENTS

There is an old Eastern fairy tale about three clever, lucky princes, darlings of fortune, who, in wandering about the wide world, 'were always making discoveries, by accident and sagacity, of things they were not in quest of.' The princes were from Serendip (the old Arabic name for the island of Ceylon), and this story inspired Horace Walpole to coin the term 'serendipity' for the faculty of making happy and unexpected discoveries by accident.

Serendipity is a faculty of true scientists. It often happens in science that you are in quest of one thing, but thanks to chance, a lucky coincidence of circumstances and shrewdness, something quite different, but much more important, is discovered. The history of science, however, like the old tale of the three princes of Serendip shows that this gift is bestowed on inspired and profound minds and that it is only the flash of genius and good training that enables them not to pass over a lucky accident with indifference but to turn it into a discovery.

So chance is not merely chance, and serendipity is not simply a lucky coincidence.

We will not give you examples of falling apples, shouts of 'Eureka' when the water overflows the bath, mysterious blue glows suddenly glimmering in a laboratory shed and ushering in a whole new branch of science. Suffice it to recall the exciting story of the discovery and study of elements heavier than uranium, the heaviest one that 'completes' Mendeleev's Table, the story of the first synthetic elements made by man, which had either disappeared from the face of the earth long ago or had never existed at all.



Fermi's team in Rome, 1934. Left to right: Oscar D'Agostino, Emilio Segrè, Edoardo Amaldi, Franco Rasetti, Enrico Fermi

It all properly begins with serendipity one sunny morning in 1935. In the low, cool vaults of the University of Rome young Enrico Fermi, already a world-famous physicist, and a quartet of his best friends and colleagues, Edoardo Amaldi, Oscar D'Agostino, Franco Rasetti, and Emilio Segrè were looking, won-

derstruck, at the 'work in hand'—an unpretentious experimental chamber in which they hoped to produce new elements heavier than uranium by bombarding the latter with neutrons.

For a neutron gun they used a small sealed glass tube containing beryllium powder and a radioactive gas (radon) that, like radium, emitted alpha particles (nuclei of helium), which were needed to obtain free neutrons. Alpha particles (approximately one per hundred thousand) hit the nucleus of a beryllium atom, uniting with it to form a carbon nucleus and liberate a neutron. Fermi and his colleagues needed free neutrons as projectiles to force their way into Nature's main citadel, the atomic nucleus.

By that time Fermi and other physicists were already well aware that the atom, Nature's principal building material, consists 99.999999999 per cent of free space. In a neutral atom light, negatively charged particles, or electrons, circle in outer orbits about a positively charged nucleus, the volume of which is around 10^{-12} that of the atom, or less. Almost the whole mass of the atom is concentrated in the submicroscopic nucleus, and its density is tremendous (240×10^{12} grams per cubic centimetre). The weight of a cubic millimetre of substance of comparable density would be approximately 100 000 tons. If our houses were built exclusively of atomic nuclei, fifteen standard ten-storey blocks would weigh as much as the whole planet.

The atomic nucleus is known to consist of heavy, positively charged particles, or protons, and of neutrons, which are identical with them in mass but have no charge (and which had been discovered by James Chadwick two years before Fermi's experiments).

The number of protons in a nucleus determines its charge, and consequently the number and arrange-

ment of the orbital electrons balancing its positive charge. Thus an atom as a whole is neutral.

The number of its electrons and their arrangement in orbits determine all the chemical properties of an atom, all the countless combinations of elements, and all the chemical reactions that underlie the infinite variety of the world of living and non-living matter. Electrons also determine the positions of the elements in Mendeleev's Periodic System. The Periodic System is no longer an empirical law of chemistry. Having become firmly grounded in the theory of atomic structure, it has acquired a simple but very essential physical sense and become a basic law of atomic physics. Proceeding from the data now known to science, one can say without exaggeration that it is the only universal law of the structure of matter discovered by man, and the only one sufficiently simple to be universal.

D. I. Mendeleev, the creator of the Periodic Law, used to joke that one must observe certain rules even when picking mushrooms. The principles underlying the structure of matter discovered by him opened up dozens of ways for people to look for and deliberately produce new building materials of the Universe, and opened the door to Nature's magic kitchen.

The chemical properties of the atom, then, depend on the structure of the outer electron shell, which in turn is almost wholly determined by the nuclear charge. So it follows that the position of an element in the Table is directly dependent on the number of protons contained in the nucleus of its atoms.

By 1935 both physicists and chemists had gained quite a clear picture of the role of neutrons, the other main components of the nucleus, which act as a 'cement' binding it into a single whole. Free neutrons are electrically neutral, which allows them to pass

through the strong barrier of positive electricity surrounding the nucleus. Once in the nucleus, however, they can, in certain conditions, expel an electron and a neutrino and become protons. A neutron can also 'knock' a positive charge out of one of the nuclear protons and convert it into a neutron, itself becoming a proton. Because of this interconvertibility neutrons and protons share the name 'nucleons'. The total number of protons and neutrons in the nucleus of an atom determines its mass number A.

It had already been known since 1910-2, thanks to the work of the English physicists Frederick Soddy and J.J. Thomson, that the atoms of many elements had 'relations'.

These cousin-atoms or, as Soddy christened them, 'isotopes' (occupying the same place) have the same number of protons in their nuclei, and consequently, of electrons, but a different number of neutrons. In other words, isotopes have a similar electron shell but a dissimilar nuclear filling. So, though having identical chemical properties, they differ in physical properties (different mass and different stability). For example, in addition to hydrogen with a mass number 1, there also exists in nature, as a slight admixture of ordinary hydrogen, a hydrogen of mass number 2 (deuterium), the nucleus of which (a deuteron) contains one proton and one neutron. The constituent of all living matter, carbon, has radioactive isotopes that disintegrate after a certain period, emitting radiation, and also stable isotopes, viz. carbon-12 ($Z=6$, $A=12$) and carbon-13 ($Z=6$ and $A=13$).

But Nature skilfully guards her main secret, the charged atomic nucleus. It is practically inaccessible and it seemed impossible to penetrate it. The intranuclear forces retaining nucleons in it are immense

and still incomprehensible. They successfully withstand electric forces. Coulomb's law, which is now about two centuries old, says that the force of repulsion between two bodies of like charge is proportional to the magnitude of the charges and inversely proportional to the square of the distance between them. This implies that the smaller the distance between the charged bodies, the more strongly they repel one another. The distance between positively charged protons is as little as 10^{-13} centimetre. Soddy calculated that two grams of protons placed at opposite poles of the earth would repel one another with a force of 26 tons. If the force of repulsion were not countered by the immeasurably greater force of nuclear attraction, all the atoms of the Universe, except hydrogen, would disperse, forming a gigantic hydrogen cloud.

The force of nuclear attraction can operate only at very close distances commensurate with the diameter of the atomic nucleus.

Fermi and his colleagues, knowing that it was the atomic nucleus that held the answer to Nature's most important mysteries, sought in every way just to open the door to it the slightest bit. To do so they employed a remarkable property of slowed-down neutrons, their ability to penetrate the barrier of atomic forces unhindered. Atoms are as transparent to neutrons as a glass ball to light rays. They virtually do not interact with electrons and can move inside a substance, colliding only with nuclei, without losing any energy. A neutron, however, can interact with nuclei no matter how great the speed at which it is moving. Having collided with a nucleus, it either changes direction or penetrates the nucleus, causing a nuclear transformation.

Free neutrons, however, do not travel where they

are aimed though they very occasionally do so. To ensure that they did Fermi devised his own apparatus.

When surplus neutron enters an atomic nucleus, it causes it to undergo a transformation. If the neutron (upon emitting an electron) turns into a proton, the nucleus, having become one unit heavier, will be converted into its right-hand neighbour in the Periodic Table, that is a new element will be produced.

Fermi's group subjected every element, then known, beginning with hydrogen, to bombardment by their neutron gun. After a long chain of disappointments, when they achieved nothing, or next to nothing, the sunny spring day came at last on which the atomic hurricane broke. The gun bombarded the heaviest element then known in the Mendeleev Table, uranium, with neutrons.

Fermi and his co-workers had supposed that when the uranium nucleus, packed to the limit with 146 neutrons, gained one more neutron, one of them would be converted into a proton. Thus element 93, with a nucleus containing 93 protons and 146 neutrons (which did not exist in nature) would be created artificially.

And in actual fact, in Fermi's experiments, the uranium bombarded with neutrons from the little glass gun was transmuted into radioactive elements never before observed. But what were they? Though the *New York Times* published an article about an Italian producing element 93 by bombarding uranium, Fermi himself, and the world's most eminent scientists, racked their brains over this mystery for another five years.

On 10 December 1938 Fermi was awarded the Nobel Prize for physics 'for the discovery of new radioactive elements produced by neutron bombardment, and for the related discovery of nuclear reactions induced by slow neutrons'. On 11 February 1939

Nature published a sensational letter from Lise Meitner and Otto Frisch, under the heading 'Disintegration of Uranium by Neutrons: A New Type of Nuclear Reaction'.

The unusual radioactive elements obtained by the Rome group were not transuranic elements at all, as was established by the scrupulous experiments of Otto Hahn and Fritz Strassmann and confirmed by Frisch's experiments, but in fact only radioactive isotopes of the well-known light elements barium, lanthanum, and cerium, with a mass half that of uranium. It was an event that radically altered the history of mankind.

Fermi's group, without knowing it, had managed to do something no one had ever dreamed of: they had split a monolith of incredible density, the atomic nucleus, by means of nothing more than a tiny neutron! As someone aptly put it, it was equivalent to shattering a granite rock by tapping it with a pencil. And the 'rock' did not simply break apart but in doing so released the immense energy locked up in it.

For the first time there dawned before humanity the breath-taking prospect of releasing and then utilizing the most powerful energy in nature. The formula of this century, Einstein's famous equation $E=mc^2$, was being turned into the practical means to revolutionize technology. For one gram of uranium can liberate an amount of energy equivalent to that obtained by burning 2000 kilograms of oil or 2500 kilograms of the best coal. And as an explosive, one kilogram of nuclear substance is equivalent to 20 million kilograms of TNT.

The Nobel Prize, Fermi used to joke later, had been awarded for the first time for an experiment that had been wrongly interpreted. The experiment itself put such enormous power into man's hands

that all the leading laboratories throughout the world naturally concentrated on studying the artificial fission of atomic nuclei induced by neutrons and investigating the processes that accompanied it.

Artificial fission became Problem No. 1. There is no need to repeat here what everyone now knows, since it is common knowledge that the peaceful atom was born in the Soviet Union, where (in 1954 in the town of Obninsk) current from the world's first atomic power station was first fed into the mains. Atomic engineering has become an independent industry while nuclear physics, the science of the atomic nucleus, has continued to develop. No one would be bold enough to predict how many wonders and surprises it still has in store for us. After all, serendipity is a promising faculty of any true science.

FIRST STEPS BEYOND URANIUM

The mysterious element 93 turned up when least expected.

Excited by the news of the great discovery of nuclear fission, scientists in various countries busied themselves devising basic experiments that would enable them to obtain additional information about this remarkable phenomenon. In 1940 Edwin McMillan at the Radiation Laboratory in Berkeley (California) was trying to measure the distance the fission fragments of uranium could travel in matter. He took some leaves of ordinary cigarette paper and stacked them together to form a little book. On the top leaf he put a very thin layer of uranium dioxide, leaving the others to act as a screen to stop the fission fragments. The whole book, with its uranium cover, was put into the target of a cyclotron and

Edwin McMillan, who discovered the first transuranic element

subjected to neutron bombardment. Separating the papers after irradiation, McMillan measured the radioactivity of each leaf by means of a Geiger counter. And then, all of a sudden.

He got the results he was looking for. But, as he relates, it also turned out that the by-product or side-effect was much more important than the initial experiment.

In this case the by-product was that the sheet of cigarette paper coated with uranium contained a radioactivity with a different half-life and different properties from those of the fission products in the other sheets.

And McMillan had an idea they might belong to another element.

At this point, Dr.P.H.Abelson, an old friend of McMillan's, came to Berkeley from Washington on

his summer holidays. Instead of lazing about he spent his days with McMillan at the laboratory bench trying to identify the chemical properties of the unknown substance found in the first leaf of paper. To the surprise and joy of the two enthusiasts it appeared to differ in chemical properties from any known element and called for the introduction of changes in the Periodic Table.

Thus, at last, the first element heavier than uranium had been discovered. They named it neptunium. It filled place 93 in Mendeleev's Table since it contained one proton more than uranium.

In 1951 Dr. McMillan was awarded the Nobel Prize jointly with Dr. Glenn Seaborg (who had continued his work) for the discovery and study of chemical elements with atomic numbers greater than uranium and coming after it in the Periodic System (and for that reason called transuranic elements).

What was it about the first transuranic element that so astonished scientists?

At the beginning of the 40's the elements in the Periodic Table were not only listed in order of their atomic numbers but also arranged in groups that embraced elements with similar properties. Neptunium should have occupied the 93rd space directly beneath rhenium, and alongside uranium, which at that time lay below and in the same column as tungsten. It had been supposed that neptunium would have properties similar to those of rhenium. But McMillan and Abelson found, to their great surprise, that it was not in the least like rhenium and resembled uranium much more than would have been expected, differing very little in its properties from the latter.

Anticipating events, let us note here that this fact and others we will be discussing later made it neces-

sary to review the arrangement of all the heaviest elements in the Periodic System and helped to bring out new patterns in it.

It was of interest, of course, to obtain even heavier elements. It was a question of No. 94, of whose existence there could be no doubt. The nucleus of neptunium was radioactive, that is could decay by emitting electrons (which always involves the conversion of a neutron in the nucleus into a proton and increases the positive charge of the nucleus).

Thus nuclear physics developed another important trend, the production (synthesis) and study of superheavy atomic nuclei. This trend was led at the time by the American radiochemist, Seaborg, then head of the Radiation Laboratory at Berkeley, and by Fermi's colleague and pupil Emilio Segrè. In the late 50's the centre of this most interesting research moved to Dubna, a town near Moscow where, under the leadership of G. N. Flyorov, member of the USSR Academy of Sciences, it was taken up by the international team of scientists of the Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research.

The science of transuranic elements has, in turn, greatly stimulated the development of nuclear physics, prompting new directions for research, to say nothing of the wealth of new methods, instruments, and techniques that has been brought into being in the heat of this absorbing quest.

What does it mean, to produce new elements that disappeared from the face of the earth long, long ago? It means vying successfully with Mother Nature herself.

Man tries to create new nuclei according to a previously considered plan and his own recipes. For centuries the old alchemists spared no efforts stri-

ving, by means of ingenious manipulations, to find the magic 'philosopher's stone' in order to transmute base metals into gold.

The 'philosopher's stone' proved to be the atomic nucleus. But can present-day scientists transmute any material into gold?

Now that they know the structure of the nucleus it is possible, in principle: a proton here, an electron or a neutron there, and Bob's your Uncle. As soon as any substance has 79 protons packed into the nuclei of its atoms, it will jump over to position 79 in the Periodic Table and acquire the noble symbol Au. 'But it's too dull and pointless', scientists would say. 'We know all about gold and it has no special secrets for physicists or chemists. But francium, now that's something else. It has so many puzzles and can be so useful... We'd do better to use gold to produce francium. That would do science good.'

And in fact that is happening. Gold targets are the normal thing in modern cyclotrons. But that is not the point. It is much more tempting to use artificially obtained heavy elements, though that calls for large quantities, and so far only a few atoms of them have been 'won' and that by titanic efforts. Their cost is incomparably higher than that of gold.

To produce a substance according to one's own recipes one must be able literally to foresee everything, and to calculate and compare everything. It takes the main guiding thread of Mendeleev's Periodic Law to find and sort out the scores of still unfamiliar, tangled threads hidden away in heaven knows what hiding-places. In general, one has to answer millions of whats, whys, and wherefors.

The most difficult thing of all is to single out the main question among those millions. But no matter how one reckons them, they are all important and

necessary and all main ones. It is important to sort out in detail the mechanism of nuclear interactions. What happens exactly when a projectile nucleus hits a target nucleus? There is a vast number of possible reactions, depending on the energy or velocity of the bombarding nucleus, on its radioactive features, and on the character and potentialities of the target nucleus.

Nuclei can collide like two billiard balls and fly apart without suffering any change, or one may fly off while the other one stays where it was, or they can 'collide' through their electrical fields rather than directly. Either or both nuclei may gain additional energy through the interaction, i.e. become excited. And once again, they may behave in very different ways. In striving to get rid of this energy and return to a stable state, a nucleus may radiate it in the form of a gamma-quantum, an electron, a positron, or one or more neutrons; or it may 'cool down' by itself, or it may break up into pieces for no apparent reason from a negligible action, a phenomenon that is known as 'tunnel effect'. Tunnel effect cannot be exactly explained as there is nothing similar to it in classical physics. Why a nucleus, having penetrated all the barriers of nuclear and electromagnetic forces, should suddenly disintegrate, or eject several nucleons, or absorb nucleons of another nucleus is incomprehensible to anyone not up in the laws of quantum mechanics that govern the microworld.

It is as mysterious as if a ball kicked by a child were, for no apparent reason, to pass through a concrete wall metres thick. In principle that might happen, of course, but the probability of such an event is really too close to zero. With atomic nuclei, however, it happens quite frequently. Tunnel effect is a very ordinary thing in this unusual microworld.

After colliding, nuclei may exchange nucleons or may fuse to form a complex compound nucleus. And this compound nucleus gets rid of its surplus energy by various means.

It is not only the uninitiated who find it difficult to comprehend and interpret the vagaries of nuclear interactions but also the 'high priests' of the physics of the microworld, i.e. the theorists. For one has to have a good idea of the structure of the nucleus and be able to describe it accurately: how the protons and neutrons are arranged within it, how they combine, whether their distribution is uniform, how they are bound together, what is the character and strength of the interaction of free and bound nucleons, and so on. It is far from simple, for nuclei are most complicated formations. The forces operating between nucleons, as we already know, are also very complicated and still have not been sufficiently studied. And even if they had been, it is exceedingly difficult to describe the properties of a system consisting of a large, though finite, number of particles.

In order to understand the laws governing the properties of nuclei, physicists began to design simple models. What does it mean 'to design a model'? The term is interpreted rather loosely but in fact it means any set of simplifications. One has to find a model that will describe the real system with the greatest possible accuracy and permit of mathematical interpretation. Every model, naturally, singles out one aspect and explains the experimental facts for which this aspect is of paramount importance.

In 1939, when passions ran high over the problem of nuclear fission, the famous Danish theorist Niels Bohr, author of the theory of the atom, and John Wheeler, of Princeton University, advanced a hydrodynamic or liquid drop model, treating the

nucleus as a drop of liquid. Independent of them, in 1936-9, a Soviet theoretical physicist, Jacob Frenkel, developed a fuller and more detailed electric drop theory that likened an excited nucleus to a charged drop of boiling water.

The formation of a sphere demands the least expenditure of energy, and a drop of water is a sphere. Just as molecules of water form drops of various sizes, so protons and neutrons give rise to various atomic nuclei. By adding energy to a drop of liquid it can be elongated and it will remain so as long as the forces of surface tension are able to keep it whole. At a certain point, however, it will become more economic for it to split in two, the excess energy being converted into heat. The forces operating in the atomic nuclei are quite different, of course, from those in a drop of water. Yet, for all that the complex compensation of nuclear and electrostatic forces can also be disturbed at a certain threshold energy, causing deformation of the nucleus. It will then also be more economic as regards energy for the nucleus to split or to resort to some form of radioactive decay—radiation of particles, or gamma-quanta.

The liquid drop model explains the resistance of nuclei to deformation quite well and predicts the limits of their stability during fission. Why, for example, do heavy nuclei divide much more frequently than light ones? The more protons there are in a deformed nucleus, the greater is the repulsive force between its parts and the less the additional energy needed for it to explode and break up. As one goes down Mendeleev's Table, from the smaller numbers to the larger ones, the energy needed to cause fission becomes less and less.

Heavy nuclei only need a fairly small amount of energy to overcome the nuclear forces of attraction

and in some cases it may happen spontaneously, without additional energy.

The liquid drop theory provided a model for the composite or compound nucleus that implied not only that all the nucleons were uniformly distributed throughout it but also that they were equally responsible for the properties of each of its specific states. When an 'alien' projectile particle hits a target nucleus, striking one or two nucleons, it loses energy to them, and, consequently, to the nucleus as a whole, before it passes on through. The energy remaining in the 'projectile' will not be sufficient to overcome the nuclear forces of attraction, so that it will be captured by the nucleus. The compound nucleus, having obtained excess energy from the incoming particle may concentrate it in one of its own particles, which will then escape.

A compound nucleus has a comparatively long life and so has time to 'forget' how it was 'born'. Its disintegration therefore does not in the least depend upon the way it was formed.

The compound nucleus theory was very successful in interpreting many experimental phenomena; the liquid drop model, thanks to its simplicity, was considered very convenient for describing the real nucleus, and played an enormous role in the study of nuclear structure. It is still used when considering fission processes in complex nuclei.

But it soon proved that the analogy with a droplet was unsatisfactory in many important cases, for example, for describing states of excitation. An excited nucleus is far from homogeneous and its constituents are not equally responsible for its state. All its parts are in continuous motion and undergo changes incomparably more complicated than the motion of particles in a drop of liquid.

The model of the nucleus as a single ensemble of very strongly bound particles, in which the length of the free path of a nucleon in nuclear matter (the mean path covered by it before the first collision) is very short compared with the size of the nucleus, proved erroneous in many respects. Much more in agreement with observations were the models, or methods, of D. R. Hartree and V. A. Fock, which looked on the nucleus as an 'association' of independent particles and supposed that the nucleons could move about almost freely in the nuclear field. Roughly speaking, such a nucleus would resemble a toy balloon in which the molecules of gas virtually did not interact. Basing themselves on the gas bubble method Maria Goeppert-Mayer, J. H. D. Jensen and others devised a nuclear shell model that unexpectedly led to striking advances. It assumes that neutrons and protons are grouped in shells, similar to the electron shells or orbits of an atom. The structure of these shells is extremely complex, and the forces and charges within the nucleus are not uniformly distributed. The authors of the model believed the nucleus could be well described if each of its nucleons was assumed to move independently in the averaged field generated by all the other nucleons. The length of the nucleon's free path would then be comparable with the diameter of the nucleus, that is to say any nucleon could pass through it unimpeded.

According to the shell model, the distribution of nucleons is governed by the Pauli exclusion principle. The shells are composed of energy levels and in any one level of the averaged field, there cannot be more than two protons or two neutrons. This very important feature of a level to some extent determines the special stability of certain nuclei with a 'magic number' of protons or neutrons, i.e. 2, 8, 20, 28, 50, 82, and 126.

The first magic number to be discovered was 82, the number of protons in the nuclei of an element familiar to everyone, lead, which is the end product of all natural radioactive transformations.

The shell model is successful in explaining not only the unusual stability of nuclei containing a magic number of nucleons but also many experimental facts relating to the properties of nuclei in both the ground and the excited states, and the peculiarities of their radioactive decay.

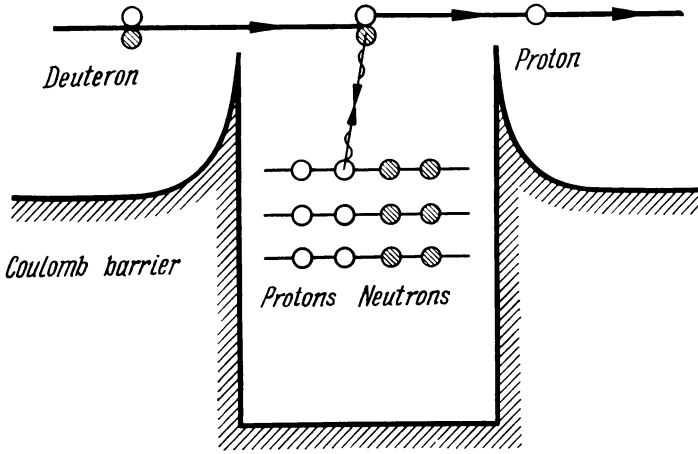
But, as with the liquid drop theory, phenomena were soon noted in experiments that it was impossible to tie up with the shell model. This time it was nuclei differing greatly from the magic number in number of protons and neutrons that spoiled the game.

It was only when Aage Bohr, son of Niels Bohr, and B. R. Mottelson proposed the collective model, which was further developed by the Soviet theoretical physicist A. S. Davydov and his collaborators, that the behaviour of these nuclei could be described.

The collective or generalized model supposes that nuclei remote from those with magic numbers have a different shape, spheroidal not spherical. In general a sphere and a spheroid are figures of the same order, as a sphere can be treated as a spheroid with equal axes.

On the example of the shell model, there are considered to be degrees of freedom in the collective model due to the motion of one or more nucleons, but at the same time, as in the liquid drop model, attention is drawn to the collective motion of all the particles in consequence of the change in shape and orientation of the nucleus.

The collective model, which is physically much closer to the shell model, explains many experimental



Direct interactions: a deuteron strikes a nucleus, its neutron is captured by the nucleus, while the proton continues its flight

findings concerning spheroid nuclei and enables some of their properties to be predicted.

If we base ourselves on the relative independence of nuclear particles, an optical model serves very well to describe interaction of particles with the nucleus. The analogy of this model with classical optics is based on the fact that nuclear particles penetrate the nucleus much as light rays pass through optical lenses; and it employs purely optical terms like 'optical density of the nucleus', etc.

When a projectile particle, immediately after entering a nucleus, collides with a resident particle, and the latter escapes owing to the energy it has received, we have a direct reaction. But if a particle, having gained energy, goes on to collide with others like a billiard ball, transferring its acquired energy

to them, the chances of any one particle gaining enough energy to escape are much reduced and a compound nucleus is formed. This explanation of the way a compound nucleus is formed is less difficult and complicated in the independent particle model than in a model of strong and uniform interactions based on the analogy with a drop of liquid.

Recent research indicates that the most accurate description of nuclear structure is provided by an independent particle model taking residual interactions into account. By residual interactions we mean the behaviour of nucleons conditioned by the behaviour of each and every particle in the nucleus, i.e. internucleonic reactions that give rise to various collective events within the nucleus.

The development of such a model has been greatly facilitated by the mathematical methods developed by J. Bardeen, L. N. Cooper, and J. R. Schrieffer, and independently by the Soviet mathematician N. N. Bogolyubov, for the theory of superconductivity, and which have enabled a superfluid model to be constructed. Research carried out on this model in Copenhagen, Dubna, Moscow, Paris, and Berkeley provided an explanation of nuclear properties that had not been given by any previous model. In fact it describes any experimental observations linked with the ground state of nuclei or a state of weak excitation.

It is most important, it seems, that the models constructed are not mutually exclusive but, on the contrary, are complementary in a way and help to disclose many details of nuclear structure; but with each one only individual details and some of the forces and processes operating between nucleons within the nucleus are revealed. Each model is concerned solely with the forces it takes as the main ones, for-

ces less important for the given processes being either neglected or very roughly taken into account.

And although physicists have now learned to determine which processes are of greatest significance in various conditions, and have come to understand the relationship between them and see the limitations on the applicability of models, a rigorous and consistent theory of the nucleus still does not exist. Only the spectra of about 5 per cent of all existing nuclei have been studied experimentally and the data on them are far from complete.

It is of first-rate importance, naturally, to find a way of bringing the various models together and to begin creating a unified theory of the nucleus, the more so that this is associated with another major problem of great importance, that of nuclear radioactivity.

As a matter of fact, what is radioactivity? That would seem to be a simple question (one can find a chapter on radioactivity in any school physics book and few fields of knowledge can boast such an abundant literature), but science is still unable to give an exact and exhaustive answer despite the fact that many interesting things have been learned since radioactivity was discovered and that knowledge of this phenomenon has come a long way.

Scarcely was radioactivity known than that physicist of genius, Albert Einstein, prophetically said that it was the most revolutionary force of technological progress since prehistoric man discovered fire.

Figuratively speaking, radioactivity is the means by which an atomic nucleus transmutes itself into the nucleus of another element. Science already knows several ways this can happen: alpha radioactivity, or the simultaneous emission of two protons and two neutrons (i.e. a helium nucleus with a charge of 2);

certain forms of beta radioactivity (i.e. the emission or capture of electrons or positrons) known occasionally to accompany the transition of a neutron into a proton or vice versa; proton radioactivity, when the nucleus emits a proton (two-proton radioactivity involving the emission of two protons has been predicted in theory); gamma-decay; and spontaneous fission. We will consider the secrets of these transformations later in greater detail, and so will limit ourselves here to their enumeration.

The discovery and study of radioactivity helped us to understand how the atom is built, and to penetrate its nucleus and, of course, enabled us rapidly to extend the boundaries of Mendeleev's Periodic Table. Without knowledge of radioactivity it would have been impossible to discover isotopes, and in general there would have been no science of the atom.

Credit for this discovery, one of the greatest in man's history, belongs to the French physicist Henri Becquerel. As usual it did not happen without serendipity. On the advice of his colleague, the well-known mathematician H. Poincaré, Becquerel performed several experiments to elucidate the peculiarities of phosphorescence (the cold luminescence of certain bodies), wanting to find out whether it was accompanied with X-rays.

On 24 February 1896 Becquerel wrapped a photographic plate in black paper and put it in sunlight with a uranium salt on top of it. When, after a time, the plate was unwrapped and developed, he found it to be fogged and noticed that the image of the salt was clearly imprinted. He decided to repeat the experiment the next day, but was unable to expose the plates to sunlight, as it remained cloudy the whole day. So he put the plates away in a drawer of his desk, still neatly wrapped in paper with ura-

nium salt. For a whole week the sun did not shine in Paris and Becquerel could not continue his experiments. On March 1st he decided to develop the unexposed plates in order to check the purity of the plates themselves and consequently of the experiment. The dark contours of the samples could be easily distinguished on them. The uranium compound was emitting rays itself without the aid of sunlight! That was how natural radioactivity was discovered, i.e. the capacity of elements to decay spontaneously emitting radiation.

Within a few years scientists could already differentiate three modes of radioactive transformation of elements. Then the existence of radioactive isotopes was established. But to get to the heart of this phenomenon and really to use this guide to Nature's treasure-house could only be done by accumulating and expanding knowledge of the atomic nucleus. In fact, we can easily trace how each new step deeper into this field brought with it appreciable progress in mastering the secrets of Nature's 'magic' kitchen.

By 1869, when the Periodic Law was discovered, only 63 elements were known, and then only the stable ones, i.e. their stable isotopes.

Between 1875 and 1886 three more elements were discovered, as correctly predicted by Mendeleev from his Law. In the last decade of the nineteenth century some of the rare-earth elements and the five inert gases were discovered and identified.

As soon as the results of Becquerel's experiments on natural radioactivity had been published, discoveries of hitherto unknown radioactive elements followed one after another, and some elements that had been well known for a long time were found to have such unexpected radioactive properties that they were treated, like uranium, as if newly discove-

red and underwent a second birth. Such was the case with thorium, uranium's neighbour in the Table.

When, in 1828, the chemist and naturalist, Jöns Jacob Berzelius, christened the new element he had separated from a mineral thorium after Thor, the Scandinavian god of thunder and lightning, he was not of course suggesting that it possessed magic properties and by no means associating it with the thunder of explosions. Thorium owes its second birth to the great French scientists, the Curies, who detected its radioactivity in 1898-9.

While studying the radioactive properties of uranium and uranium salts and minerals, Marie Curie isolated two quite new radioactive elements from uranium ore that were hundreds of times as radioactive as uranium itself. In July 1898, in the French journal *Comptes rendus* there appeared a communication about the discovery of the first of these elements, an analogue of tellurium, precipitated from a solution in hydrochloric acid by means of bismuth sulphide. Marie Curie called the new element polonium after her native land, Poland. Six months later, in the same journal she published the first information on another radioactive element, radium, whose properties fully corresponded with Mendeleev's prediction and proved to be close to its chemical analogue, barium.

In 1899 André Debierne, an associate of the Curies, discovered yet another element, actinium. The most remarkable thing about it was not only that he had not isolated it but that he had not observed it either. Debierne had deduced its existence from the products of its radioactive decay, which were also radioactive. A year later, and independently of Debierne, actinium was discovered by the German chemist F. O. Giesel, who demonstrated its similarity to lanthanum.

It was extremely difficult to study actinium at that time. Its infrequent occurrence and the poor sensitivity of the equipment then available, made Soddy, the 'father' of isotopes and greatest student of radioactivity, write ten years after its discovery: atomic number unknown; average lifetime unknown; radiation none; mother substance unknown; the starting material seems to be uranium; disintegration product radioactinium.

Only later was it shown that the actinium isotope discovered decayed emitting beta particles of very low energy.

In 1899 and 1900 the constituents of radioactive radiation were determined: namely, alpha, beta, and gamma rays.

In 1900, too, Ernest Rutherford, who first discovered the atomic nucleus, detected with Soddy the breakdown product of a radioactive element in radium preparations, the result of the transmutation of one element into another, which they called emanation. At first they believed the emanation to be three new inert gases, but it subsequently became clear that they were chemically inseparable varieties of one and the same gas, radon.

In 1901 europium was discovered and in 1903 gallium was detected as a product of the radioactive decay of radium. In 1907 lutecium was discovered. And in addition to these, there was a host of unnamed elements.

Soon 30 radioactive substances regarded as chemical elements were competing for the eight vacant places in Mendeleev's Table. The avalanche threatened to engulf the periodic law. Luckily, Soddy (Nobel Prize for chemistry) suggested, in 1910, the existence of twin-nuclei, different versions of the same element, and called them isotopes. As we already

TABLE 1

Mendeleev's Periodic Table of the Elements Constructed on the Basis of Bohr's Atomic Model (at the time when scientists were still making their first attempts to obtain transuranic elements)

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	(43)	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La | Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	(85)	Rn
(87)	Ra	Ac	Th	Pa	U	(93)	(94)	(95)	(96)	(97)	(98)	(99)	(100)				

↓

La	Ce	Pr	Nd	(61)	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu

know, they had absolutely the same nuclear charge and chemical properties, but different atomic weights and physical properties. Following this discovery experiments to determine nuclear charges brought the number of known elements to 86.

By the beginning of the Thirties there were only four unfilled places left in the Periodic Table (with atomic numbers 43, 61, 85, and 87), and the whole series closed with uranium (92).

But was this the last one? Did the Periodic Table have to close there? Could there not be elements heavier than uranium? What would their properties be? To predict them at that time was very difficult as next to nothing was known about them. Mendeleev believed there could be at least five elements heavier than uranium, but he did not express any views about their possible chemical properties. On the basis of the model of atomic structure proposed by Niels Bohr the arrangement of elements in the Periodic Table was altered a little (see Table 1), so that there were now only six elements in the row beginning with number 87, namely: 88 radium, 89 actinium, 90 thorium, 91 protactinium, 92 uranium. It was only natural to suppose that the blanks would be filled. But how? Would the new family be analogous to the lanthanide series? What element would it begin with?

Various researchers advanced different propositions. Kanematsu Sugiura and Harold Urey, for instance, believed that the progenitor should begin with atomic number 95, whereas Maria Goeppert-Mayer proposed protactinium or uranium. In the fifteen years from 1926 to 1941, incidentally, all the elements from 89 to 95 inclusive, without exception, were suggested as the beginning of the new family. During those same fifteen years chemists in various countries

were trying to find natural transuranic elements. R. A. Loring and Druse, using X-rays, deduced mysterious lines in pyrolusite and attributed them to element 93. In 1934 Cobblin reported discovery of 'bohemium', with an atomic weight (mass) of 240; and in 1938 Horia Hulubei and Koshua 'secovanium'.

All of these communications remained unconfirmed. Preconceived opinions of the hypothetical chemical properties of the new elements were not the least cause of error.

Most chemists expected the element with atomic number 93 to be chemically analogous to rhenium. The true nature of isotopy was not yet sufficiently clear, though after the discovery of a nuclear particle, the neutron, by the English physicist, Sir James Chadwick, a former student of Rutherford's, conceptions of the atomic nucleus made an immense qualitative leap.

We can say without exaggeration that the neutron proved the magic key that helped us to penetrate into that mysterious and unassailable citadel, the atomic nucleus. For in the long run, it was the neutron that gave man his first opportunity to reshape matter at will and create new atoms. And as it turned out, it was necessary to create them.

The elements missing from the Periodic System could not be found, not because they were badly sought after but because they did not in fact occur in nature. Having been formed some five thousand million years ago along with all the elements of the solar system, they did not survive to our day as they had been transmuted into other nuclei as a result of radioactive decay. In order to study their properties it was necessary to recreate them.

Not two years elapsed after discovery of the neutron before another very great discovery was made that

has had no little influence on the history of mankind. In 1934 the French scientists, Irène Joliot-Curie, the daughter of Marie and Pierre Curie, and her husband Frédéric Joliot-Curie discovered artificial radioactivity and found a way of changing well-known stable elements into radioactive ones, giving them a radioactivity no less than that of natural radium.

By bombarding aluminium, magnesium, and boron with alpha particles emitted by natural radioactive elements the Joliot-Curies obtained radioactive isotopes of the common stable elements phosphorus, silicon, and nitrogen. It gradually became clear that the atoms of almost all the elements responsible for the diversity of nature around us have radioactive twins whose radiation enables us to trace their movement within even the most complex systems. We shall not enumerate all the practical consequences here of the remarkable work of the Joliot-Curies, but there is not a field of science or technology where artificially-radioactive labelled atoms have not been employed. For us it is no less important that the work of Irène and Frédéric Joliot-Curie became a turning point in the development of nuclear physics.

It was after Fermi, studying the behaviour of artificial radioactivity by means of neutrons (in the experiments mentioned above), discovered a way to use neutrons as bombarding particles and the American Ernest Lawrence built apparatus in which electromagnetic fields enabled charged particles to be accelerated to high energies that the synthesis of new elements could be attempted.

Since neutrons could be produced, for example, by bombarding beryllium or some other light element with alpha particles, any researcher who had at least a hundred thousandth of a gram of radium at his

disposal could transmute elements and study what happened.

The first synthetic element was discovered and identified by Segrè and his colleague, the mineralogist Carlo Perrier.

In 1937 Segrè visited the excellently equipped laboratory of the University of California in Berkeley and took back to his little laboratory in Palermo samples of molybdenum that had been bombarded on its small, recently built accelerator or cyclotron not with neutrons but with deuterons, nuclei of the isotope of hydrogen, deuterium. Segrè and Perrier supposed that molybdenum, which had 42 protons in its nucleus, after bombardment with deuterons (which have one proton and one neutron) would be transmuted into element 43 with 43 protons in its nucleus. In the Periodic Table this element should be located in the column that includes rhenium and manganese, and be chemically analogous to them.

After many laborious operations that Segrè himself considered equivalent to extracting ore from a mine by hand they isolated an unknown substance and demonstrated chemically that it was not any known chemical element, though, as had been supposed, it was very like rhenium. This was the first element created by the hands of man, so Segrè decided to call it 'technetium', which means artificial.

The next artificial element, with an atomic number of 85, was astatine, an unstable element obtained in 1940 also by Segrè (who had emigrated from fascist Italy to America) and his colleagues at Berkeley, Dale Cordon and K. R. MacKenzie.

Segrè, naturally, proved to be among the first who tried to produce elements heavier than uranium. But, as we know, the transuranic elements had more than

once treacherously and cunningly tripped up the most astute researchers in the first attempts. It had also happened to Segrè. In 1939 he had observed that two radioactive elements with half-lives of 23.5 minutes and 2.3 days were formed in a thin target of an ammonium-oxygen uranium compound after bombardment with fast neutrons. The first was uranium-239 but there were extremely few atoms of it. The other radioactive isotope behaved in a very peculiar way. It was not precipitated when rhenium (in the view then commonly accepted considered to be chemically homologous to the new element) was used as a carrier. Instead of being precipitated by hydrogen sulphide from a strongly acid solution with rhenium, the 'capricious' element was precipitated, for no obvious reason, with lanthanum fluoride.

Segrè's short report of this experiment published in the *Physical Review* concluded that the transuranic elements had not yet been discovered. By the irony of fate it was Segrè himself who refuted his greatest discovery, the synthesis of the first transuranic element, because he could not escape from the toils of traditional views that element 93 must be analogous to rhenium since, according to the Periodic Table, it should be found directly below rhenium.

The following year, 1940, McMillan and Abelson (who, as we know, discovered element 93) repeated Segrè's experiment and found that what had been formed was neptunium.

Having studied the chemical properties of the new element, they established conclusively that neptunium was not chemically homologous to rhenium but resembled uranium and lanthanum in its properties, as Segrè also had established.

Twelve isotopes of neptunium are now known. All of them are radioactive. The first appreciable

amounts of the longest-lived of them, neptunium-237 (with a half-life longer than two million years), sufficient for research, could only be produced at the end of 1944, when Chicago University's first nuclear reactor was built. The difference between neptunium and uranium is so slight that scientists had to look critically at the arrangement of the heaviest elements in Mendeleev's Table.

RIDDLES OF THE TRANSURANIC ELEMENTS

This facilitated the search for the next, 94th element in many ways. McMillan and Abelson established that neptunium emitted beta particles in decaying. Consequently, the decay product must be the next element with one more proton, that is element 94. It was discovered late in 1940 by Seaborg, Arthur Wahl, Joseph Kennedy, and McMillan after bombarding a uranium target with deuterons in the 60-inch cyclotron at Berkeley used by Segrè for technetium and McMillan for neptunium. The new element was named plutonium. No one then suspected that it would become the star of the transuranic elements.

The production of new synthetic elements raises three quite different problems of equal importance. The first is how to synthesize and obtain atoms of the new element, the second is to determine its properties or, as scientists say, to identify it, i.e. to obtain irrefutable confirmation that the element produced is the one being sought. The third problem is to isolate it, i.e. produce it in sufficient quantity for chemical investigation. The last problem, it seems, is probably the most difficult. The heavier the element, the shorter is its life, the more difficult it is to get

in quantity, and the more complicated the investigator's job.

The first isotope of plutonium obtained in the winter of 1940 was plutonium-239 with a half-life of 24 000 years. Another isotope plutonium-238 with a half-life around 90 years was also obtained at Berkeley in the winter of 1941.

The decisive experiment was mounted in the small chemical laboratory on the campus of the University of California on February 23. For the first time a visible quantity of the artificial element was obtained. On that day the whole of the world's supply of plutonium could be put on the point of a needle. But even then scientists had a shrewd idea of an unusual property of the new-born element, that of being fissionable by neutrons. In order to study this in such a small amount of the substance, quite unusual research techniques were needed. How to weigh and measure an almost invisible quantity, two millionths of a gram? Or how to dissolve and mix a substance within a single droplet of liquid?

Burris Cunningham and Louis Werner developed the new analytical chemistry of plutonium. They built ultra-microchemical instruments designed to measure an amount a million times less than that usually manipulated in chemical research. They made capillary tubes for very small volumes of liquid, of the order of a hundred thousandth of a litre, the walls of which were lined with a water-repellent substance. They also devised tiny pipettes that filled by capillary action.

To digress for a moment, let us note that techniques for measuring extremely small volumes of liquid have found wide application in biochemistry. Certain chemical analyses of blood that used to require numerous samples, and hence a great number of ex-

perimental animals, can now be done on a single solitary mouse. With ultra-micromethods it can now be determined where, how, and why poisonous substances (e.g. insecticides) are accumulated in the organisms of insect pests, which helps to control them. Ultramicrochemical techniques have revolutionized embryology, the science of the development of the foetus into a complete organism.

The first ultramicroscopic amounts of pure plutonium compounds were weighed on a balance perfected by the Italian biochemist, E. Salvioni. A quartz fibre only three times as thick as a human hair and ten centimetres long was attached at one end to a support so that it acted like a very fine fishing rod. The other end of the fibre was bent into a hook, and from it the object to be weighed was suspended, held on a pan of very thin platinum foil. By observing the movement of the fibre through a microscope, it was possible to weigh the plutonium compound with an accuracy of hundredths of a microgram.

The ultra-microchemists joked that they had to weigh invisible material on invisible scales. But their labours were not in vain. The chemical properties of plutonium are now as well known as those of ordinary elements, and it proved to be very interesting chemically. It is perhaps the only element that has four different states of oxidation capable of existing simultaneously in aqueous solutions. A solution of plutonium is fabulously beautiful as the colour of the oxides changes as they pass from one oxidation state to another. A solution of salts of trivalent plutonium is a clear bright blue. During the transition to the tetravalent state the colour becomes a fresh green or rich honey tone. A solution of the highest, hexavalent plutonium oxide is a sunny yellow colour like a ripe lemon.

Physically plutonium-239 is much more likely than uranium to disintegrate (i.e. undergo artificial fission) when bombarded with moderated neutrons, which makes it more valuable as nuclear fuel.

1942 had come, that hard year in the Second World War. Almost all Western Europe was choking under the fascist jackboot. The flames of battle blazed over a vast expanse of the Soviet Union from the Neva to the Volga. The Nazis were preparing to invade Great Britain. Japanese submarines were attacking American ships in the Pacific Ocean. Czech uranium was being taken to Germany in sealed railway vans. In occupied Norway a heavy-water plant was working at full capacity. In the USA a group of physicists had been working in strictest secrecy for over two years on designing an atomic bomb. Even closer secrecy was clamped down on all work with plutonium. On the basis of the research carried out on an ultramicrochemical scale a big war factory had been built at Hanford (Washington) to separate plutonium. Plutonium was disclosing unlimited potentialities for employment for either the detriment or the good of man. Unfortunately, the world learned of them only when the plutonium bomb was exploded over the Japanese city of Nagasaki.

With the building of nuclear reactors in which, as a result of chain reaction of nuclear fission of uranium, it proved possible to obtain a powerful flux of neutrons that, used to bombard uranium, produced plutonium, modern alchemy got its industrial start. Plutonium was the first, and is still the only synthetic element produced by the kilogram; total production has increased a million million million times in 25 years.

Having completed the most important chemical experiments connected with producing plutonium,

Seaborg, Ghiorso, James, and Morgan turned to synthesis of the next transuranic elements, 95 and 96. But the business of extending the limits of Mendeleev's Table did not prove as consistent as could have been wished.

It was more like a route march than a hike, Seaborg and Ghiorso relate. A tough battle for an objective had to be followed by a period for bringing up reinforcements (in the form of new information and techniques) before assaulting and capturing the next objective.

The interval occasionally lasted five or six years. So it happened this time. Years passed and all attempts to obtain and identify elements 95 and 96 suffered fiasco. Failure followed on failure. The dramatic situation with neptunium repeated itself. The researchers built their experiments on the data of the Periodic Table as it stood at that time and the Table implied that the chemical properties of elements 95 and 96 should bear a strong resemblance to those of neptunium and plutonium. But uranium, neptunium, and plutonium (as had been established by 1944) could be considered chemical 'cousins', though their degree of relationship was not yet clear. It could be supposed that the new, very heavy family of elements began with uranium and formed a 'uranide' series (i.e. 'like uranium'), and the researchers were guided by that in their long and fruitless quests. The undiscovered elements stubbornly would not fit into the niches intended for them in Mendeleev's Table.

It was only at the end of 1944 that Seaborg conceived the daring idea that the elements heavier than actinium were perhaps not correctly placed in the Table. He boldly advanced an original hypothesis that came to be known as the actinide theory. It was that all the elements heavier than actinium formed

The Periodic Table as It Appears Today — TABLE 2

(The atomic numbers of elements still undiscovered are shown in brackets)

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-71 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89-103 Ac	104 Ku	105	(106)	(107)	(108)	(109)	(110)	(111)	(112)	(113)	(114)	(115)	(116)	(117)	(118)

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	Lanthanide series
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 (No)	103 Lr	Actinide series

a special series similar to the rare-earth or lanthanide elements and should be shown separately in an extended row below them (see Table 2).

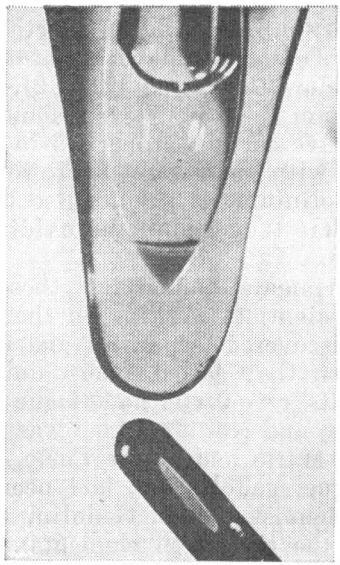
On the basis of these new ideas elements 95 and 96 should both have certain properties in common with actinium and with their rare-earth 'relatives', europium and gadolinium. It should also be characteristic of them that they cannot be oxidized above the trivalent state.

When experiments embodying these views were mounted the scientists working on the Berkeley cyclotron soon discovered (separated and identified) element 95 (which they called americium in honour of America, as its rare-earth homologue europium honoured Europe) and No. 96 (which was named curium in memory of Marie and Pierre Curie, since its rare-earth homologue, gadolinium, had been named after the Finnish chemist, Johan Gadolin, the pioneer of research into the rare-earth elements).

Americium was obtained by neutron bombardment of a plutonium target. The plutonium, having captured a neutron, became heavier, then captured another neutron, and emitted an electron from its nucleus as one of the 'extra' neutrons was converted into a proton, thus forming the nucleus of americium.

Curium, too, was first synthesized by bombardment of a plutonium target, but this time with helium ions (two protons and two neutrons) instead of neutrons. The plutonium, having captured two protons and two neutrons, became two units richer in charge and, having emitted the 'extra' neutron, was transmuted into curium with a mass three units greater.

With the guiding thread of the actinide theory, which neatly established that all elements beyond actinium up to No. 103 belonged to one family and had similar properties, it became clear to Seaborg,



Photograph of one of the first samples of americium hydroxide obtained (visible in solution at the bottom of the capillary tube). The head of an ordinary needle is shown below the tube for comparison

Ghiorso, Kenneth Street, Jnr., and S. G. Thompson just where and how they should look for them all. But understanding did not make the job any easier. Theoretically everything should have been simple: bombard americium with helium nuclei ($95+2=97$), one or two neutrons would be emitted and there would be the new element. Similarly, bombardment of a curium target with helium should yield element 98. The only snag was where to get the amount of americium and curium needed to make the targets. Nearly five years were spent trying to obtain them. In 1950

the americium oxide stored in a vial the size of a sixpence was considered a very respectable stock. As we have already said, the higher the atomic number of an element, the less stable it is, the more readily it disintegrates, and the greater is its radioactivity. A trifling amount of curium dissolved in a capillary tube no bigger than one's little finger is so radioactive that it can be photographed in darkness.

For all that Seaborg's team at Berkeley prepared the required targets in 1949-50 and having bombarded them with alpha particles in the same cyclotron, discovered the two new elements numbered 97 and 98. It was found that they, too, were close in chemical properties to their suggested rare-earth relatives. Element 97 was named berkelium after the city of Berkeley, California, where it was discovered (in the same way as its rare-earth analogue, terbium, had been named after Ytterby in Sweden, where the rare earths were first found). Element 98 was named californium. Californium is chemically similar to dysprosium (which means 'difficult to get at'). Its 'godfathers' explained their choice of name not only by their wish to immortalize the state and university where the element was first discovered and identified, but also advanced a weightier argument: 'The best we can do is to point out ... that the searchers for another element a century ago found it difficult to get to California.'

The new element was identified from an infinitesimal amount containing not more than 5000 atoms.

The first weighable amount of californium (a little more than 2×10^{-9} gram) was separated at Berkeley in July 1958.

Clearly, one could not even dream of a target of californium. It was necessary to think of a substitute. But what? Luckily, serendipity came to the rescue. The story of the discovery of elements 99 and 100 is

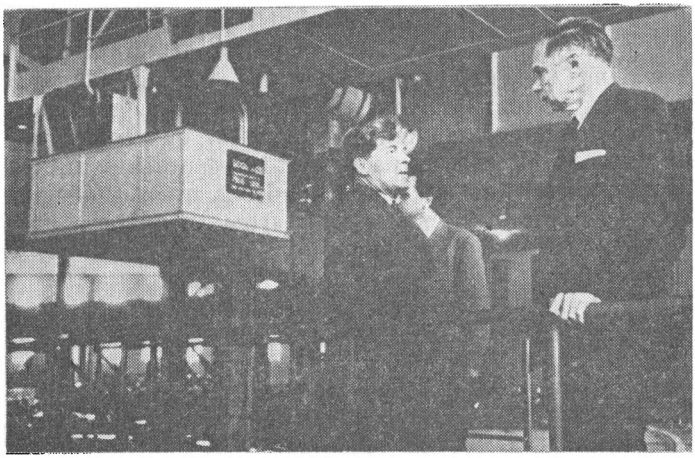
another striking example of unexpected results in science.

It was 1 November 1952. A small atoll in the South Pacific was lovingly reflected in the emerald waters of its lagoon. The feathery serrated silhouettes of the coco-palms barely swayed against the pearly dawn sky. Then suddenly there was an unbearably bright flash, and a fiery dazzling whirlwind with a terrifying hissing that rose to a deafening howl. In a fraction of a second the peaceful island was turned into an infernal bowl filled with molten, evaporating lava. It was called 'Operation Mike', the notorious thermonuclear explosion of 1952. On board battleships and cruisers of the U. S. 7th Fleet, scientists and military observers watched from a safe distance how the island was melted and incinerated and reduced to a glass crater a mile wide. The gigantic white radioactive cloud rose at great speed to the stratosphere and covered the atoll with a deadly canopy a hundred miles across.

A fortnight later it fell out in rain. A peaceful fishing boat was caught by it. Japanese housewives were forced to use portable Geiger counters before choosing their fish at Tokyo's famous fish market.

But that was later. Now, in accordance with the 'Operation Mike', radio-controlled pilotless planes were flown into the radioactive cloud. Special precautions were taken when they returned to the aircraft carrier; they were sprayed down with water and deactivated by special techniques. The game was worth the candle. The special paper filters attached to the planes successfully sampled the lethal cloud for laboratory analysis by which scientists would be able to explain what happened during a thermonuclear explosion.

The first unexpected reports came from the Argonne



Glenn Seaborg (right), Nobel Prize winner

National Laboratory and Los Alamos, where the atomic bomb was first made. The filters of radioactive material contained new, as yet unknown, very heavy, neutron-saturated isotopes of plutonium.

Scientifically, this was quite unexpected. It implied that during the instant of a thermonuclear explosion uranium could successively capture not just one or two neutrons but a great many, for its nuclei were subjected within millionths of a second to the effect of a veritable neutron squall ejected by the fusing light elements. And that meant in turn that uranium could be transmuted in these conditions into heavier elements. For, as we know, a nucleus by emitting a beta particle alters a neutron into a proton and is thereby converted into the nucleus of the next element in the Table By the instantaneous successive capture of many neutrons uranium could be transmuted to californium or even heavier elements.

The group at Berkeley promptly asked for material from the explosion. Their very first attempts at separating the radioactive mixture in ion exchange columns reliably demonstrated the existence of some unknown heavy elements. But what ones? In order to learn that, it was necessary to secure amounts of the material for analysis, hundreds even thousands of times larger than available from the filters. So a new operation was initiated, which some wit called 'Paydirt'.

Hundreds of kilograms of coral were collected from an atoll near the explosion area and taken with vast precautions and in the strictest secrecy to Berkeley. But to comprehend the secret of the coral and share the impatience of the scientists, we must first consider the facilities for chemical investigation of the material.

The techniques of ion exchange and the high-speed radiochemistry connected with it (if we can call it that), had been developed under the direction of Seaborg. Its complicated sounding name conceals a simple but highly efficient method of isolating elements closely resembling each other in chemical properties.

Imagine a dark stick made of a special resin enclosed in a cylindrical glass jacket so that it can conveniently be warmed (for most chemical reactions proceed more quickly at elevated temperatures). Ion-exchange resins are insoluble organic substances that do not contaminate the solution, and have a very effective capacity for reversible exchange of ions of like charges. At the bottom of the glass cylinder there is an opening as in a pipette. A mixture of elements is absorbed by the upper part of the column, and an appropriate solvent added, which dissolves the mixture and flows drop by drop from the lower opening. One of the elements dissolves more quickly and another more

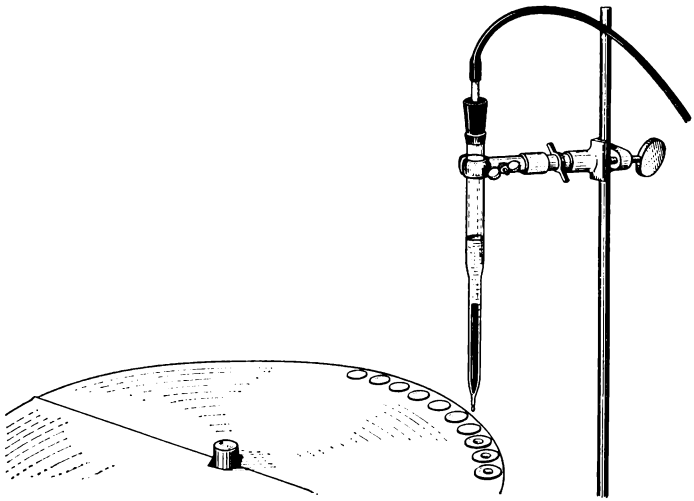
slowly and layers form in the column from the elements in the mixture. By catching the drops one can successively collect all the elements even when they are as like as two peas and there is not enough to be seen under a microscope.

Chemists who work with the rare-earth elements are very familiar with this technique. The solution dripping from the ion-exchange column is usually collected in little platinum cups around the rim of a turntable. The first few drops, the heaviest element in the mixture (in this case, for example, californium), drip from the column. Then the table is turned a little. The next drops will contain curium, then americium, and so on, until the operation is completed with the lightest one. The amount of each element in successive drops progressively decreases. The time intervals between the dripping of the various elements were accurately calculated and the amount of the element in each pan determined by radiochemical techniques. Thus the new elements could be reliably identified by their behaviour in ion exchange resins.

The technique itself, of course, is far from new. The best natural ion-exchanger, clay, constitutes the bulk of the soil and retains water-soluble fertilizers so well that even torrential rain does not leach them out.

Back in 1858 the German chemist H. Eichhorn, by mixing and drying solutions of sodium silicate and sodium aluminate, produced a white jelly that served as the first artificial exchanger. Ion-exchangers are used as water softeners; the calcium and magnesium that make water 'hard' are exchanged with their aid for sodium ions as the water percolates through an active layer.

A new era began in 1935 when the British chemists Adams and Holmes reported having made a synthetic



Ion-exchange apparatus used to separate actinide and lanthanide elements

resin possessing the properties of an ion-exchanger. Scores of ion-exchange resins specially adapted for various processes are now sold that are absolutely resistant to acid or alkaline solutions. There are some resins by which sea water can be desalinated. During the war marines and paratroops had a compact ion-exchange device, a plastic bag and six tablets, in their kit. The tablets were cation exchangers of great capacity, charged with silver ions. In an emergency, a tablet put into the plastic bag with half a litre of sea water would turn it into drinkable water. The silver ions combined with chlorine ions and were precipitated, and could easily be filtered out with cheesecloth.

Ion exchange is also employed to 'soften' cow's milk for babies, removing the excess indigestible calcium. It is also used to purify the beet syrup from which sugar is refined. It is even used to treat ulcers of the stomach; an anion ion-exchange resin taken internally stimulates rapid neutralization of hydrogen ions, i.e. reduces the acidity of the stomach.

In biological research ion exchange is probably the sole method both for separating complex mixtures of closely similar amino acids (which are the constituents of proteins) and for isolating nucleic acids, which are so similar in properties that they cannot be separated by any other means.

Seaborg was the first to find a way of employing ion-exchange resins to separate infinitesimally small quantities of highly radioactive elements. He did an enormous amount of work to find the appropriate solutions and calculate how long it took each element to elute, or wash out, and precipitate.

The Berkeley scientists shovelled hundreds of kilograms of radioactive coral grain by grain into ion-exchange columns. The 'dirt' proved an 'El Dorado'. The very first drops gave positive identification of elements 99 and 100, though they contained less than 200 atoms of element 100.

The group of workers from Berkeley, the Argonne National Laboratory, and the Los Alamos laboratory involved in discovery of these elements suggested calling element 99 einsteinium after the creator of the theory of relativity, Albert Einstein, and element 100 fermium to perpetuate the name of Enrico Fermi.

In order to obtain isotopes of einsteinium and fermium for research by a method less devastating than a thermonuclear explosion, they had to bombard grams of plutonium with an extremely powerful flux of neu-

trons. Later it became possible to use heavy ions instead.

The 60-inch cyclotron at Berkeley was too small for the purpose. It could only be done in a nuclear reactor, exposing plutonium to bombardment by neutrons for a long period (between two and three years). Only a super-thermonuclear explosion with its intense neutron flux could shorten the process to millionths of a second!

The plutonium to be bombarded was alloyed with another metal and encased in aluminium. The canned alloy was then moulded into rings that would cool easily. The rings were put into the active zone in the very heart of the reactor, and the heat resulting from nuclear fission was removed by washing them with water.

Some of the plutonium, successively capturing bombarding neutrons and emitting beta particles, decayed into americium, which in turn captured neutrons and decayed into curium, and so on.

The 'fattening' up of plutonium nuclei with neutrons, as we already said, takes at least two years. They not only become saturated with neutrons but also undergo fission and disintegrate, which leads to the formation of highly radioactive fission products (isotopes of around half the elements that exist on earth) as well as of transuranic elements.

Because of their harmful radiation, the 'hot rings' (which were worth thousands of times their weight in gold) have to be brought to the laboratory after exposure in massive hermetically-sealed lead containers. And they can only be studied in special 'hot' laboratories provided with well shielded boxes. All operations are carried out by means of 'mechanical hands' manipulated by a scientific worker standing behind a massive defensive screen.

The shield is normally a concrete wall with a small window of lead glass tens of centimetres thick. Modern 'hands' sensitively obey the operator's movements. They can take minute samples with their pincers and put them into tiny pipettes, unscrew or screw on lids, pour solutions, and even mop up spilled solution.

All the complicated operations are completed in an ion-exchange column.

Several hundred thousand atoms of einsteinium were obtained. The platinum cup of the 'counting plate' with droplets containing einsteinium was dried and tested by means of an impulse height analyser or kick sorter, an instrument that sorts out the radiation from different elements according to its energy. The dials of its counter record the number of disintegrations of atoms of one particular element.

It was now the turn of element 101. It proved in many ways to be the most thrilling and absorbing page in the history of the Berkeley laboratory. The plan, drawing on the experience already gained, called for bombardment of an einsteinium target, by the most intense flux of alpha particles achievable in the Berkeley cyclotron. The 99 charges of einsteinium and two charges of a helium nucleus should give the desired nucleus with 101 protons.

After long trials in the reactor in Arco, Idaho, about a thousand million atoms of einsteinium, an amount invisible to the naked eye, were accumulated and isolated in the hot laboratory. Early in 1955 Seaborg's group decided to begin their experiments. No one then could envisage that the main ones were still ahead and would strain their every nerve, and that fast chemistry would literally rival the speeds of sprinters.

The nuclear reaction for bombarding einsteinium,

element 99, with helium nuclei is relatively simple:

$$\text{einsteinium } {}^{253}_{99} + \text{helium } {}^{4}_{2} \rightarrow \text{element } {}^{256}_{101} + n^{'}_{0}$$

It took place in a cyclotron, in which a beam of helium nuclei struck a small target made of a very thin disk of gold foil on the back of which an invisible layer of einsteinium had been electroplated.

If any atoms of einsteinium were transmuted into element 101 by the bombardment, they would be knocked out of the target by the impact, so a second piece of gold foil was put right behind the target in order to capture them as they were ejected.

Both target and 'catcher' were put into a special holder that had to be fixed inside the cyclotron directly in the path of the bombarding particles. The powerful stream of helium nuclei could be seen, if it was allowed to escape from the target area into the air, as a thin beam of blue light and would be photographed through the five-foot tank of water that served as viewing window into the premises housing the cyclotron.

The whole cyclotron room was sealed off while the target was bombarded. Bernard Harvey and Ghiorso waited outside the water door a great tank of water on casters.

'We were really waiting for the starting gun in a very unusual obstacle race,' Ghiorso says. This first experiment was expected to produce just one atom of element 101, or maybe two. And these one or two atoms had to be separated from millions of atoms of einsteinium and identified in less than half an hour.

As soon as they got the all-clear Ghiorso and Harvey opened the water door and ran inside. Ghiorso quickly pulled the target holder from the machine while Harvey peeled off the second bit of foil with a pair of tweezers and shoved it into a test tube. Then

he raced down the narrow corridors and up a flight of steps to a temporary makeshift laboratory where he gave it to Gregory Choppin, who heated it in a solution to dissolve the gold. So they got a liquid containing gold, various miscellaneous elements, and, they hoped, a few atoms of the element they were after.

The remaining chemical operations had to be made a mile away, 'up on the hill' at the Radiation Laboratory. For the mad dash up the hill, Ghiorso wrote, he was ready at the wheel of a 'get-away' car just outside the cyclotron building. They had (they hoped) a few atoms of element 101, and their job was to isolate and identify them before they all disintegrated. (Mendelevium is so short-lived that half of any sample decays in about half an hour, becoming an isotope of fermium, which in turn decays by spontaneous fission.)

The precious drops were taken to the Laboratory where Stanley Thompson was waiting with apparatus to separate element 101 from the einsteinium, gold, and whatever else might be present in the solution.

First the liquid was passed through an ion-exchange column to get rid of the gold, which was held back while a solution containing element 101 dripped off at the bottom. These drops were dried and redissolved and then Thompson put them into an ion-exchanger to isolate element 101 from any others that might still be present.

The drops coming from the column were caught, one by one, on little platinum plates, which were dried under an infra-red lamp, and then taken to a counting room where Ghiorso put them into special counters, one plate in each counter.

If the particular drop being tested contained any element 101 it would show up as it decayed, for when-

ever one of its atoms disintegrates the exploding fission fragments cause a big burst of ionization, and the pulse of current makes the pen on the recording chart jump.

It is typical of these elusive heavy elements, Ghiorso says, that we cannot positively identify an atom until it ceases to be that element and decays into something else. It's rather like the man who only counts his money when he has spent it.

On that anxious night during the first experiment they waited more than an hour before the recording pen jumped to the middle of the scale and fell back, marking a line that meant the disintegration of the first known atom of element 101.

Since this was quite an event at the Laboratory, Ghiorso recalled, they connected a fire bell to the counters so that the alarm would go off every time an atom of element 101 disintegrated. It was a most effective way of signalling the occurrence of a nuclear event, but quieter means of communication were soon substituted, following representations from the fire department.

The Berkeley team found only about one atom of the new element in each of their first experiments. They repeated them about a dozen times, and finished up with a grand total of 17 atoms.

But could the chemical behaviour of one or two atoms unambiguously characterize its properties? The conditions of the experiment, Ghiorso affirmed, allowed them to answer that in the affirmative. Each atom in passing through the ion-exchange column entered the same reactions (adsorption and solution) at least one thousand times, which provided a convincing statistical description of each one.

Early in 1955 the world learned of the discovery of element 101. The group proposed to call it mendele-

vium as a mark of recognition of the pioneering role of the great Russian chemist who developed the Periodic Table and was the first to use it to predict the chemical properties of undiscovered elements, and whose principle had been the key to the discovery of almost all the transuranic elements and would preserve its importance as scientists went on to very heavy nuclei.

The discovery of mendelevium was the culminating point of the story of the heaviest elements. For the next steps beyond uranium, mobilization of forces and the bringing up of reserves, it was already clear, would not be enough. It called for a new strategy and tactics.

The atoms of transfermic elements are so short-lived and are formed in such infinitesimal quantities that their chemical identification, i.e. their isolation in the pure state and determination of their chemical properties, is out of question. But that was precisely how evidence of the discovery of a new element used to be obtained. Consequently, a new technique had urgently to be found, as reliable as the old one, for detecting and identifying new elements.

No fewer difficulties also awaited researchers with the elements already obtained. All the eight synthetic transuranic elements, without exception, from neptunium to fermium, were produced, as we know, by adding neutrons to a target nucleus. Each new element so produced was then isolated in weighable amounts (in the way considered above for the 'hot' rings of plutonium) and then used, in turn, as target material for synthesis of the next element.

The cyclotron provided accelerated neutrons or projectile particles, while the target particles were produced in a reactor; and isotopes of the elements already discovered were accumulated.

'Mass production' of atomic nuclei with longer half-lives than those of the first isotopes of americium, curium and even of berkelium, discovered by means of high neutron fluxes in powerful reactors, was begun in 1954-5 and mastered by 1956-7. Decay of berkelium made it possible, a little later, to produce a mixture of californium isotopes. But these 'weighable' amounts were not visible to the naked eye, and their high radioactivity made them very hazardous for those handling them. One microgram of californium-252 emits some 180 million neutrons a minute. Even when it is being produced in a reactor special safety measures are required not to speak of work with these all-penetrating particles in the laboratory.

They still remember in Berkeley, the accident in 1959 when they were trying to obtain element 102. The window of the cyclotron blew out, for some reason or other, and bits of the curium oxide target, emitting millions upon millions of alpha particles, flew into the test room. Dangerous radioactive dust spread through the whole building. Fortunately, they succeeded in evacuating people quickly and prevented them from being irradiated. Only three weeks later, after thorough decontamination of the building, was it safe again to work in; and even much later activity was still detected from time to time in the most unexpected places.

However difficult and complicated the problems might seem, they could be solved some way or another. Even bigger efforts, ingenuity, and virtuoso inventiveness in the end would yield techniques suitable for detecting a single, solitary atom during the few minutes of its life.

The main obstacle was that the very method of producing new heavier nuclei (by successive capture of neutrons and subsequent emission of beta particles

and conversion of neutrons to protons) had become unsuitable after mendelevium.

Theoretically it was reckoned that heavier and heavier elements could be produced by intensifying the neutron flux in reactors and lengthening the period of bombardment, but in practice that proved not to be so.

Judge for yourself: however much you intensified the neutron flux, bombardment would have to go on, if not for months or years, at least for hours or days. It takes time for a nucleus to capture each successive neutron. Element 100 (with a mass number of 256) lives only two and a half hours, and mendelevium (with a mass number of 256) decays by half in 90 minutes.

Even if element 100 could successfully be produced by a powerful neutron flux it would disintegrate, even without capturing neutron, into the nuclei of two lighter elements with atomic numbers around 50, and any further addition of neutrons would be pointless.

The further we go beyond number 100, the shorter the life of nuclei. Their half-lives are reckoned in seconds rather than minutes, so that a long time for capturing neutrons is out of the question. A quite new approach was needed. But what?

Let us look a little closer.

The nine transuranic elements synthesized by that time had been produced by increasing the charge of the target nucleus each time. But this had reached its limit. Further increase was impossible. And it was also impossible to add many neutrons by successive capture.

How then was the charge on the interacting nuclei to be increased? The most reasonable and promising method, it seemed, was to try and increase the charge of the bombarding nuclei. The same target was to be

bombarded not with neutrons or alpha particles but, for example, with boron nuclei, which have five protons, or carbon nuclei with six protons, or even with nitrogen nuclei with seven protons, rather as with fast industrial building methods that use large panels or modules instead of bricks. Element 101, for example, might be obtained by using a target, not of the exotic einsteinium of which there is fantastically little, but of the more available americium, and bombarding it with six-proton carbon.

It was a natural, almost obvious idea but scores of difficulties soon arose of course. In order to see what they were and learn how they were overcome, let us turn our minds from the Radiation Laboratory in Berkeley to the Kurchatov Institute of Atomic Energy in Moscow.

HEAVY IONS

In 1953 the Kurchatov Institute did not yet bear Kurchatov's name. He was still alive and the head of it, and his bubbling energy and scintillating ideas inspired the work of all its research groups. G.N. Flyorov, his pupil and closest colleague from pre-war days, was selecting enthusiastic young people from among the graduates of the recently founded departments of nuclear physics in Moscow and Leningrad in order to expand work on producing and studying superheavy elements.

'What would you like to work at?' Flyorov asked Vitaly Karnaukhov, a newly fledged physicist with a brand-new diploma.

'Nuclear physics,' Vitaly answered resolutely.

'O.K.' Flyorov agreed. 'Start work tomorrow.'

In much the same way he recruited Victor Druin,

I.V. Kurchatov, Member of the USSR Academy of Sciences

and thoughtful Sergei Polikanov, Nicholas Tarantin, Yuri Oganesian, and others.

Work began for all of them, in fact, the very next day, very real, quite independent work that called for unusual inventiveness and complete involvement.

'We are going to produce elements that do not occur in nature,' Flyorov told them. 'To do that we need ions. Not simple ions but multiply charged ones, accelerated to very high energies. Science doesn't yet know where to get them or how to accelerate them. There are only suppositions. Would you like to think on it?'

Ions are electrically charged atoms. An ordinary atom is electrically neutral. The positive charge of

its protons, as we have already said, is fully balanced by the negative charge of the electrons orbiting around the nucleus. If we strip one or more electrons from an atom or, on the contrary, add surplus electrons to it, it will accordingly acquire a positive or a negative charge and be converted into an ion. Depending on the number of electrons lost or gained, the ion will be singly, doubly, or multiply charged.

Many substances are combinations of ions, common salt for example. It consists of a positive sodium ion that has lost one electron and a negative chlorine ion that has captured this electron. Between oppositely charged ions immense electrostatic forces of attraction operate. If we could find the means of separating the sodium and chlorine ions in a gram of salt and put the one at the North Pole and the other at the South Pole they would still attract each other with a force of several tons.

Why are ions needed for reactions with heavy nuclei, and not atoms? Two types of forces, as we know, operate between atomic nuclei: namely, nuclear forces of attraction, which come into play only after nuclei are in surface contact; and electrostatic or Coulomb forces of repulsion acting over considerably greater distances, which prevent them from doing so. Nuclei can only overcome the electrostatic barrier that follows from Coulomb's law (known as the Coulomb barrier) if they have sufficient velocity (which is determinable from the same law). An idea of the energy involved can be obtained from the fact that, in the bombardment of uranium with oxygen ions, it is about 90 million electron-volts (90 MeV). That means that special machines are needed—particle accelerators. But all existing accelerators impart energy to particles by means of electromagnetic fields and cannot affect neutral atoms. Consequently, only charg-

ed particles can be accelerated. In the Berkeley 60-inch cyclotron, mainly the charged nuclei of the lightest elements (hydrogen and helium), i.e. deuterons and alpha particles. were accelerated.

So one had to design an accelerator for heavy ions, which proved unbelievably difficult.

First of all it was necessary to find some way of accelerating heavy ions to the energies needed to overcome the Coulomb barrier. But that was not all. If the number of new high-energy ions was insufficient, reactions would occur very seldom, which meant that it was necessary to contrive to produce very powerful ion beams. At the same time it was necessary to meet the following contradictory requirement: the larger the charge of a particle, the higher are the energies to which it can be accelerated by an electric field, but the greater its mass, the lower, naturally, is its acceleration at the same energy. The ratio of its charge to its mass (i.e. its specific charge) determines the acceleration of a particle, and, consequently plays a most important role in the design of an accelerator. For protons the specific charge is unity ($Z=1$, $A=1$); for deuterons and alpha particles 1:2 (for deuterons $Z=1$; $A=2$; and for alpha particles $Z=2$, $A=4$). The specific charge of heavy ions is always less than unity.

The energy imparted to a charged particle in a cyclotron is proportional to the square (a) of the intensity of the magnetic field, (b) of the radius of the angular velocity to which the particle is accelerated, and (c) of its specific charge. This implies that, when a heavy ion and a proton or an alpha particle are accelerated in the same cyclotron and at the same intensity of the magnetic field, the energy imparted to the ion will be much less than that imparted to the proton or alpha particle. Thus, if the energy of alpha particles, for

example, is 28 MeV, then doubly charged nitrogen ions will be accelerated to 9 MeV.

To increase the energy of ions it is necessary to raise the intensity of the magnetic field, i.e. the power of the magnet of the cyclotron. But that cannot be done indefinitely because of the peculiarities of the design of conventional electromagnets. That being so it is necessary to increase the radius of the ion's orbit, in other words, to increase the size of the cyclotron. That is why a heavy-ion accelerator has to be much bigger than a conventional charged-particle accelerator of comparable energy.

In spite of these difficulties, no one, it must be said, was put off from trying to realize such alluring possibilities. In 1940 the American physicist Luis Alvarez was already trying to accelerate hexa-charged hydrogen ions in the 36-inch cyclotron at Berkeley. He succeeded in obtaining an energy of 50 MeV, but the resulting beam was so weak that physical research was ruled out at that time, the more so that cyclotrons could provide beams of protons, deuterons, and alpha particles of an intensity of 10^{13} to 10^{14} particles per second.

How was beam intensity to be increased? It took decades to find out.

At first the so-called stripping method was tried. A normal ion source is roughly a thick-walled gas-filled chamber containing electrodes (a cathode and an anode). When voltage is applied to the electrodes, an ordinary electric arc—or powerful discharge—occurs between them. The electrons emitted by the cathode are accelerated in the arc and bombard the atoms of the gas, ionizing them and changing it into plasma.

Normal sources can easily supply singly and doubly charged ions. But, as we have already explained, the

greater its charge, other things being equal, the greater the energy gained by a particle. Therefore it is better to accelerate multiply charged ions.

If doubly charged ions are injected into a cyclotron operating initially below its basic frequency, they will collide during acceleration with atoms of the residual gas in the vacuum chamber, lose some of their electrons, and become hexa-charged. They can then be accelerated in the normal way, at the basic frequency, to the energy required. High-energy multiply charged ions with a beam intensity of tenths or hundredths of a microampere, which is adequate for many experiments, have been obtained in this way in Great Britain, the USA, Sweden, and the USSR.

Unfortunately, however, inherent trouble developed that wiped out all the advantages of this method. As the transition of ions from the low-charged state to the multiply charged one proceeded all over the chamber and at different times, the particles reaching the target had a diffuse energy spectrum; while fine experiments require mono-energetic beams—otherwise it is out of the question to estimate the energy of interaction with any definiteness and to calculate its possible results.

The cyclotron could provide mono-energetic heavy ions only if they were accelerated immediately at the basic frequency, without charge exchange with atoms of the residual gas. That called for much larger accelerators than existed and also for powerful sources of multiply charged ions; but early in the Fifties no one had even dreamed of them. For that reason, and a number of others, the Americans under Seaborg and Ghiorso abandoned cyclotron (orbital) techniques of accelerating heavy ions, counting them inexpedient, and preferred to to use a linear accelerator in which

all the ions could be 'stripped' simultaneously in two separate stages.

In the early linear accelerators low-charge ions were first accelerated, then stripped in a special device, and sent on their way as multiply charged ions. To control these processes highly sophisticated radio-engineering equipment was employed. The first accelerator of this type began working in the USA in 1957, and a little while later a second, more powerful one, known as HILAC (Heavy Ion Linear Accelerator).

With linear accelerators carbon ions with an energy of 120 MeV could be obtained. The initial intensity of the beam was 0.05 microampere, but various improvements and more accurate adjustment gradually raised the current to 0.5 and even 1.0 microampere.

A MACHINE FOR 'MAKING ATOMS'

Flyorov's team in Moscow adopted quite another approach. They preferred, in spite of all the difficulties, still to use a cyclotron to accelerate heavy ions since, once the difficulties were overcome, it offered inestimable advantages; a reason of no little weight was the fact that a 150-centimetre cyclotron was then already working at the Institute of Atomic Energy. The physicists decided to adapt it to their ends.

It was quite clear that an ion source of unprecedented power, which could 'strip' atoms efficiently, i.e. multiply charged ions, must be 'top of the bill'. Heavy ions could then be accelerated in the ordinary way without recharging in the cyclotron, and a beam obtained for experimental purposes.

To accelerate low-charge ions, pole pieces of too great a diameter would be needed and, consequently,

a magnet of unreasonable size. To accelerate a doubly charged neon ion to the necessary energy of 140 MeV, for example, would require a cyclotron with pole pieces 12 metres in diameter and weighing tens of thousands of tons.

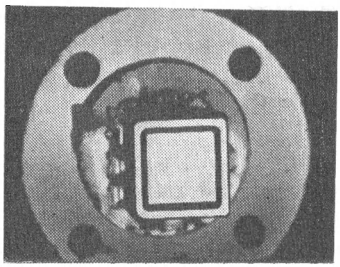
B. N. Makov, A. S. Pasyuk, and Polikanov cannot help smiling now when they recall how they worked in small basement rooms soldering, assembling, and selecting materials, changing conditions again and again to adjust a source designed to separate isotopes in a mass-separator to their cyclotron. On the wall hung a placard announcing in large hand-painted red letters: '102 Will Be Ours!' A small bulletin under the placard gave a progress report on who had done what that day.

In 1953-4 no one except those doing the work, and of course, Flyorov and Kurchatov, took that bit of fun seriously. The country's major nuclear institutes were studying nuclear fission, and busy designing processes and developing reactors. The world's first industrial atomic power station in Obninsk, near Moscow, was being groomed for starting up.

That was considered the main trend and the main forces were concentrated on it. Even the late Prof. Leo Artsimovich, member of the Academy of Sciences, later the 'God of plasma', was then absorbed in these problems. And here was Flyorov, a pioneer of research into fissile materials, suddenly occupied with problems that seemed so far from reality. It needed the scientific perspicacity and intuition of Kurchatov to appreciate and extrapolate the probable significance of Flyorov's 'bit of fun'.

'We rang Kurchatov up at all times of the day or night,' Flyorov recalls. 'But we couldn't do it over trifles, so we had to make do as best we could.'

By 1955 the source was ready. It was a gas-dischar-



Gas-discharge chamber seen from the side facing the cathode

ge chamber made of thick furnace copper well cooled by water. The chamber had two cathodes: a heated main one, and an auxiliary reflector made of molybdenum set in a copper plate, also water cooled. The walls of the chamber served as anode. The chamber was filled with nitrogen, the gas whose ions were to be produced first. The cathode was heated by electron bombardment from an incandescent tungsten filament. In the powerful arc discharge atoms of the gas were stripped down to ions with several charges. In order to strip off the greatest number of electrons and make the ion as multiply charged as possible, it was vital to get electrons of high energy at the cathode, and higher than the electron binding energy of the gas. An arc of great power was also necessary as the high-energy electrons from the cathode had to be emitted in a dense flux. The charged ions were to emerge through a narrow window (2 mm $\times$20 mm) in the chamber wall. The optimum size for the window had required painstaking selection, altering, and testing. A window narrower than two millimetres passed too few ions, while a very wide one (4-5 mm) made the source

work badly because of the effect of the high frequency of electric field.

After long bench trials the source was finally fitted to the cyclotron. And as usual dozens of things needed adjustment and alteration. The magnetic field in the tests had been 4000 oersteds, but was 19 000 in the cyclotron, which immediately changed the ratio of voltage and current in the arc. Fortunately, all the difficulties were successfully overcome.

The new source could produce quadruply charged carbon ions, penta-charged nitrogen ions, and penta-charged oxygen ions.

The experiments began and completely justified their hopes. The multiply charged ions were accelerated in the cyclotron into a uniform mono-energetic beam. By Oganesian's calculations, the difference at the output was under 4 per cent.

Intensity, too, was very high. The beam of quadruply charged carbon ions was of the order of five microamperes, that of the penta-charged nitrogen ions about one microampere, and that of the penta-charged oxygen 0.5 microampere.

Elated by their success, the physicists got on with their experiments.

'If we'd known then what we know now, we wouldn't have dared to begin such experiments,' Druin jokes.

But then they were emboldened. They still had to fiddle about with the targets and cooling devices, and rack their brains over techniques, but for all that, they at any rate began to get transplutonic elements one after the other and succeeded in disclosing and explaining some of the secrets of the inter-relations of heavy ions and nuclei.

Still the red letters on the poster called: '102 Will Be Ours!' With element 102 everything involved immense work. There were still very many unexplained,

obscure, enigmatic things in the behaviour of accelerated heavy ions and the response of target nuclei. The nuclear reactions needed more thorough and detailed study. And much more intense ion fluxes were wanted, as it was necessary to strip atoms down to six, seven or eight charges and to obtain accelerated ions of much heavier elements.

In March 1958, in the picturesque town of Dubna, on the Volga near Moscow, the first scientific conference on nuclear reactions with multiply charged ions was held in the newly completed hall of the House of Scientists in newly named Joliot-Curie Street, by the recently founded Joint Institute of Nuclear Research, scientific centre of the socialist countries for study of the atomic nucleus. Apart from Soviet scientists, the participants of the conference included representatives of research organizations in Bulgaria, Czechoslovakia, the German Democratic Republic, Hungary, Mongolia, Poland, and Romania.

The morning session of March 11 was opened by the Deputy-director of the Institute, Prof. V. Votrub from Czechoslovakia:

'We hope a new laboratory of nuclear reactions, fully meeting the objects of our International Institute, will be functioning next year. Now we must make thorough preparations for its work, discussing all the aspects and difficulties of studying heavy nuclei by means of multiply charged ions.'

'Our experience of work with extremely powerful ion sources on the 150-centimetre cyclotron of the Kurchatov Institute of Atomic Energy', Flyorov declared, 'has enabled us to draft and develop a scheme for a new cyclotron specially designed to accelerate heavy multiply charged ions. The apparatus, which will be built at the Joint Institute in 1959, will have a radius-to-field-intensity ratio approximately half

as big again, or double that of conventional cyclotrons. That will let us produce fluxes of all multiply charged ions a hundred or more times as powerful. And by going over to hexa- and hepta-charged ions, we shall be able to accelerate considerably heavier elements, in addition to nitrogen and oxygen. If the final adjustments are successful, we shall have every ground for hoping that the series of accelerable ions will be continued up to iron, and perhaps further. Multiply charged ions will make it possible to do qualitatively new things in nuclear physics. I would say that these are the only particles suitable at present for studying highly excited nuclei and filling the gaps at the end of the periodic system. But successful work on the transuranic elements calls for raising the strength of the beams, which we hope to do with the new installation.'

'How do you expect to tackle the ever decreasing yield of the distant elements?' An. N. Nesmeyanov asked; to which Flyorov replied: 'By increasing the intensity of beams and the weight of the projectiles and targets. Now, with not very high intensities, we are in a position to produce element 102, but there are too many difficulties. The yield of the next elements is expected to be smaller still. A ten- or hundredfold increase would make the job much easier. We would be able to do experiments with daily exposures instead of hourly ones.'

At the evening session on March 12, I. M. Motora, one of the co-authors to the scheme, talked about the new accelerator.

'As a matter of fact, our accelerator is a classic cyclotron. On the simple principles worked out by Lawrence back in 1930 and developed independently by both Wexler and McMillan in 1945-6, the charged particles pass through the same accelerating section

many times, gaining a small portion of energy each time. The most important item in the cyclic accelerator is the magnetic field, which is primarily used to produce the closed circular orbits. In big installations like ours, particles make many orbits during acceleration, travelling thousands of kilometres. Any perturbation can easily knock them aside. It is impossible, of course, to ensure ideal conditions for their movement because, owing to the imperfections of vacuum technology, there isn't an absolute vacuum in the accelerator's chamber, and because of the heterogeneous magnetic properties of the materials the electromagnet is made of, and of inaccuracies in assembly. Nevertheless, all this has to be co-ordinated so that particles are deflected as little as possible from the calculated ideal trajectory or, if deflected, are forced back to the trajectory. Only then will the accelerator work. The means for forcing particles back onto the ideal trajectory are the configuration and intensity of its magnetic field.

'The basis of our machine is an iron electromagnet shaped like the head of a trident, with cylindrical poles. It weighs 2200 tons and has a pole diameter of 310 centimetres. It should provide the axially symmetric field needed to accelerate heavy ions, i.e. maximal in the centre and falling off gradually toward the periphery. At a distance less than the diameter of the poles it begins rapidly to fade out.

'What is bothering us? In classic cyclotrons gradual attenuation of the magnetic field has pluses and minuses. On the one hand, the attenuating field bends the trajectory of the particle back to the mean plane of the accelerator. On the other hand, this form of field worsens the conditions for particles to accumu-

late energy, since the resonance character of the acceleration is disturbed. When you are dealing with heavy ions these normal difficulties are sharply aggravated because of the forced working regimes of the cyclotron.

'With the designed field intensity of 19 000 to 20 000 oersteds the radial drop will strongly affect acceleration. That makes it necessary to boost or shim the field somehow, that is to put additional masses of iron (or shims) at the edge of the magnet in order to intensify the field there and get the optimal configuration.

'The strength of the magnetic field is determined by the magnetization current in the two main windings, which consist of 224 coils each. Maximum strength (19 000 oersteds) can be obtained with a current in the windings of 2600 amperes. To accelerate ions of different kinds the field can be varied from 16 500 to 17 500 oersteds.

'The vacuum is expected to meet exacting requirements....

'A rather large chamber (75 cubic metres) will have to be evacuated to a pressure of a hundred thousandth (10^{-5}) of a millimetre of mercury. That will be done by six oil-diffusion pumps, with a capacity of 20 000 litres a second each. We have succeeded in getting one litre of pump capacity per litre of evacuated volume.

'How are we going to get acceleration?

'In this cyclotron, as in others, it will be done by means of an electric "boosting" field, sinusoid variations in which will provide the resonance contour of the radio-frequency accelerating system. The chamber will consist of two duants or dees (boxes open on one side), tanks, and a high-frequency generator.

The frequency of the generator will be carefully held constant, to a fine tolerance (up to 0.01 per cent). The amplitudes of the accelerating voltage will be quite large (300 000 volts at an earthing potential on the dees of 150 000 volts).

'What is there to say about the dees?

'This very important unit of the accelerating system of our cyclotron is unique in size, over four metres long and about 1.6 metres wide. These huge boxes, secured at one end only, must be very stable and retain a given position for a long time without deviating even a few millimetres from the horizontal and without sagging or becoming deformed.

'First of all, a special design of dee has been developed with additional stiffening; the main beam of the framework, for example, is shaped like a bent rectangular box. Secondly, the shape of the dee has been chosen so as to provide maximum opportunities for experiment.

'The specific feature of our cyclotron is the high flux of heavy ions from the source. Some of the ions are low-charge and take no part in acceleration. These "parasitic" ballast ions bombard and greatly erode the draw-out or exhaust electrode. Cyclotrons ordinarily employ a cooled slit electrode made of copper. In a cyclotron for multiply charged ions such an electrode would be rapidly and effectively eroded away by the intensive ion bombardment.

'We are looking for a design of slit optics sufficiently stable under ion bombardment. It would seem best to install a massive, well cooled, copper electrode with erosion-resistant molybdenum plates.

'The cyclotron will operate in either constant or pulsed conditions, with the frequency adjustable within a wide range. The main principle underlying our scheme is to provide maximum freedom for fur-

ther improvement of the machine and to have reasonable resources in case they are needed. For instance, though we are designing a machine with an A/Z ratio of seven, we have allowed all the same for reserves of current and of the magnet excitation unit such as would enable this ratio to be considerably increased.

'It will be possible to get ions up to krypton with charges of seven, eight, or nine units. True, there are difficulties not only in producing multiply charged ions, but also in identifying them, since their A/Z ratios become nearly identical the heavier the ions and the higher the multiplicity factors of the charge. With ions like penta-charged neon-22, hexa-charged aluminium-27, or nonuple-charged argon-40, for example, the A/Z ratios are respectively 4:40, 4:50, 4:44. But the cyclotron will be able to separate ions with a difference in A/Z ratio of the order of 0.2 per cent.'

* * *

June 1959. A dusty, windy afternoon. On the blocked Moscow-Dmitrov highway drivers were venting their impatience with angry hooting. Up the middle of the road crawled a heavy lorry. On its trailer, under a tarpaulin, was a bulky cumbersome object. And ahead of it rode a police escort on motor-cycles. Through the lorry's windows next to the driver, could be seen the tired, tense faces of Oganesian and Boris Zager. Though they had tried hard to slip through and clear the highway by dawn before the traffic was heavy, they had not managed it. They had been forced to go across country, round railway bridges and cross-overs. Any 15-ton bridge was too fragile and unsafe a structure for the 40-ton component of

the giant magnet. And the railways had refused to accept it for carriage as too bulky.

So here they were transporting it 'in bits'. The total to be taken to Dubna was over 2000 tons.

When all was said and done, transport of the magnet was the simplest and easiest of the jobs that Oganesian and his friends had to cope with in installing, adjusting, and starting up this unique accelerator. Everything they were doing was being done for the first time. No one knew anything, everything had to be played 'by feel'. The calculations were one thing, but it verged on sorcery to fit this enormous machine together and assemble it not on paper but in fact. Eyewitnesses allege that Yuri Oganesian actually displayed the qualities of a magician and wizard; there are no other words to describe the boldness, resolution, and intuitive feel of the engineer that this able physicist suddenly exhibited, to everyone's amazement, in setting-up their precious brainchild.

'We'll stick to the plan. If it doesn't work, we'll alter it ourselves,' he would say, resolutely suppressing the doubts and jeers of the sceptics, quickly grasping the situation and finding the best way to eliminate each 'fault' discovered. The ion source was found to wobble; specially strong clamps had to be devised immediately. Then the dees were sagging, disrupting operation of the accelerator; a slightly curved design with the faintest of bends was worked out that gave mechanical rigidity without affecting the alignment.

At last it was done and the first beam was fired. With early joy came new worries. The field strength was not what was expected and the current was too weak. Increasing the current, however, immediately started lightning flashing in the central section of

the cyclotron where the ion source was located: breakdown! The continuous flux of ionized gas affected the vacuum, but optimum extraction of ions called for an increase in field strength. The result was one breakdown after another. They had specially chosen a design for the central section and carefully adjusted the electrode system so as to obtain the optimum combination of the highest ion currents and a reliable vacuum gap during intensive ion bombardment.

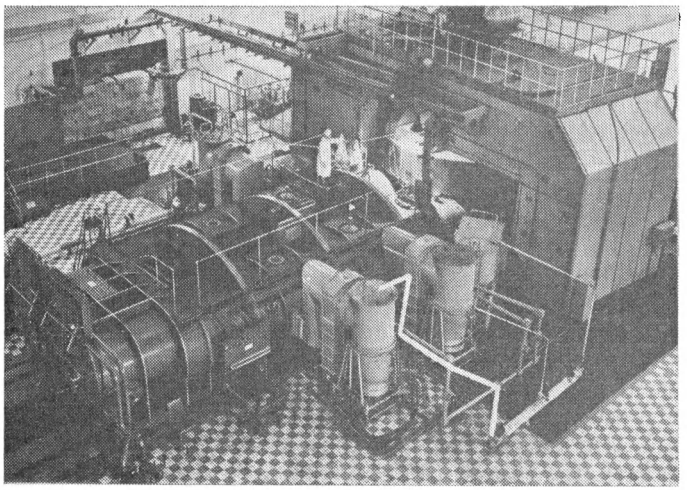
But one clear tranquil autumn morning proved, perhaps, the most dramatic, the day when, after almost a year of faultless operation, the beam for no obvious reason suddenly disappeared. The cyclotron displayed not a sign of life and would not react to the subtlest approaches and ruses. It did not work, and that was that. For two days everyone in the laboratory searched for the cause. Early in the morning the door of the director's office, suddenly opened and the duty operator, his eyes round with horror and bewilderment, burst in where Flyorov, Lobanov, Vyalov, and Oganesian utterly exhausted after covering a blackboard with formulas and smoking countless packets of cigarettes, were napping, some in armchairs, others on hard chairs.

'Georgy Nikolaevich,' he said, addressing Flyorov and hardly opening his trembling lips, 'the cyclotron is falling to bits!' And, disregarding propriety, he collapsed onto a chair.

Twenty seconds later the whole staff of the laboratory had gathered around the cyclotron, and in another thirty seconds even theorists began to arrive from neighbouring laboratories.

Under the pole of the magnet wound a distinct and ominous crack.

'Now you've done it!' someone said spitefully.



The Dubna cyclotron for multiply charged ions

'How could you think of applying such a field? No wall could stand it, let alone a magnet.'

Fortunately, a quick check showed that both the walls and the magnet and cyclotron had stood up well to everything and that the crack was due to a badly welded pole.

What was to be done? Should they dismantle the pole and take the whole great thing back to the works again and repeat Oganesian's odyssey?

They decided to do the job on the spot. The physicists and chemists spent half a year poring through books on welding, looking for ways to eliminate the residual magnetic fields, which were so great that they caused arcing during welding. The method decided on was simple and reliable. They scattered tacks over the magnet's pole, which were firmly attracted by

the magnetic field, and then passed a current through, raising and lowering it by manipulating the controller until the tacks began falling off.

What could that mean? To be sure, everything did not go swimmingly and manna did not fall from heaven. The main thing, however, was that the cyclotron was working again. And how it worked now! Every epithet for it could be preceded by 'most'. It really was unique, this biggest, most powerful, most accurate, and most reliable multiply-charged-ion accelerator (CMSI), the like of which had never been seen anywhere outside Dubna!

Now, having seen that the cyclotron method was the simplest, most reliable and effective way of producing intense accelerated beams of heavy ions, other countries, too, began building them.

Eighty- and 88-inch cyclotrons have been brought into use in the United States (at the Oak Ridge National Laboratory, and the Radiation Laboratory at Berkeley) and a 200-centimetre one in Orsay, in France, and employed to accelerate heavy ions. And a 175-inch cyclotron for heavy ions is being designed at the Argonne National Laboratory in the USA.

And of course not without reason. Though particles with a much narrower energy spread than that of the inner beams of the cyclotron can be produced on linear accelerations, the intensity of their beam is much lower. This is also true of electrostatic accelerators of the tandem-generator type, in which acceleration takes place on the linear section as in a Van de Graaff generator through the great difference in potentials between the ends of the accelerating path.

Tandem accelerators are superior to ordinary single stage Van de Graaff accelerators in both achievable ion energy and operating convenience. The maximum

energy of tandem-accelerated particles is in the region of, or above, the Coulomb barrier which, as we shall see, is of paramount importance for observing certain nuclear interactions.

Tandems are good for high-precision work, as they provide beams of very uniform and stable energy and the possibility of continuously altering it. They are quite indispensable for super-accurate research into the structure of the atomic nucleus, but the energies attainable and the intensity of the beam are lower than with cyclotrons, and for some research, for instance for producing superheavy elements, they are inadequate.

The beam of the Dubna cyclotron for the multiply charged ions was 70 to 300 times as strong as linear ones, which means that the number of ions passing through the target in it was 70 to 300 times as many as in any other existing accelerator.

WHEN ION STRIKES NUCLEUS

So 1961 came.

The best machine in the world was operating at full pace. Heavy high-energy ions were carefully hitting the targets, and the instruments accurately recording the results of catastrophes and collisions.

What of interest had they communicated to date on the inter-relations of ions and atomic nuclei? It's not enough to have excellent tools, it is still necessary to know how to handle them and to have a clear idea of their potentialities.

The reactions between compound nuclei proved much more varied than those between the nuclei and particles (protons, neutrons, etc.). And to sort out all these very intricate processes was often not so simple.

The late Prof. Artsimovich compared study of the interaction of compound nuclei with the art of a supersleuth who tries, by examining wreckage of a motorcar, to find out the cause of an accident, reconstruct how it happened, and even to sort out who was guilty.

At the Amsterdam Conference in 1956, Dr. J. H. Fremlin described certain features of their interaction, but the data were still clearly insufficient.

But now that Soviet scientists had amassed new experimental data, the principles of these interactions had been established in general outline. All the processes brought about by heavy ions can be very provisionally divided into three groups according to the character of their interactions with nuclei: (1) elastic scattering, (2) grazing reactions, and (3) nuclear fusion.

Let us take a look at the 'hot zone' of the cyclotron, where the 'projectiles' hit the target, and try to sort out just what happens there.

Elastic scattering can be compared to 'love at a distance': the nuclei do not come into contact with each other. In nuclear terms, they are a long way from one another in the zone of operation of electromagnetic Coulomb forces of repulsion. But that does not prevent them from mutual interaction affecting one another by those same electromagnetic forces, especially when one of the interacting parties is a heavy, accelerated, multiply charged ion with high angular momentum. The electromagnetic field surrounding the ion can, for example, so 'whip up' the target nucleus's electromagnetic field that, having absorbed energy, it will begin to rotate and become excited. This is known as Coulomb excitation of the rotational level caused by elastic scattering.

In these circumstances, heavy ions naturally have

a much more significant, appreciable, and varied effect than light particles.

Electrical interactions can cause such excitation that the nucleus becomes an isomer, changes its level and, without altering its charge and mass number, acquires other radioactive properties, in particular a new half-life (which can vary within very wide limits, from thousands of years to hundredths of a second, depending on the properties of the old level and of the newly acquired one, and the energy difference between them). As a result of elastic scattering a nucleus may emit a charged particle or greatly alter its shape, and the field of a heavy ion can literally distort a nucleus, flattening it into an ellipsoid.

With grazing reactions, as the name implies, the surfaces of nuclei either come into actual contact or nearly touch one another. These reactions are also known as 'direct'. Nuclear forces come into action here but the nuclei do not fuse (the energy being insufficient for that) but due to the tunneling effect already described, stripping and capture reactions occur in which, depending on the circumstances, the bombarding particle either gives up a neutron, proton, or alpha particle to the target nucleus or captures one from it. These reactions were first observed at Birmingham University during study of interactions between ions of nitrogen-14 and oxygen-16 and aluminium nuclei.

Later Volkov, Pasyuk, and Karnaukhov worked on them under Flyorov, employing heavy, multiply charged ions.

During stripping and capture reactions the energy exchanged by the nuclei is not very large, so that the kinetic energy of the bombarding particle that has captured or lost a nucleon is not appreciably altered. Grazing reactions also include the 'shrapnel effect'

first detected by Dr. Fremlin in 1954, i.e. when the projectile particle, colliding with the target nucleus breaks into pieces, some of which capture the nucleus while others are scattered.

In grazing reactions, heavy ions may either transfer or capture several nucleons at the same time, or even a bound group or 'cluster'. Study of reactions in which nuclei exchange whole complexes of nucleons yield rich information on surface structure. For the probability of one, two, or more nucleons being stripped or captured greatly depends on their mutual arrangement, and also on the inherent tendency of a heavy ion to be located on the surface of the nucleus during a direct or grazing reaction and to be absorbed into it, which offers great possibilities for synthesizing new isotopes and new elements and producing nuclei with new qualities.

The higher the energy of ions, i.e. the more it exceeds the Coulomb barrier, the more complicated and varied the picture of the transfers becomes. Not only are nucleon complexes transferred from nucleus to nucleus but the nuclei themselves become excited in the process. To get rid of the excitation, the nucleus ejects a nucleon or a gamma-quantum. Just try to sort out the wheels in such a smash-up!

The higher the energy of the interaction, the greater will be the number of nucleons that will pass from one nucleus to another. With sufficiently high energy per nucleon (of the order of 5 to 10 MeV) the ion may give up so many nucleons that it is, in fact, absorbed by the nucleus. This is already the fusion reaction in which a compound nucleus is formed. Since the fusion of nuclei is considered, not without justification as we know, to be the main way of producing new elements, we shall go into it in greater detail as that will help us understand the essence of what is to come.

When the physicists of Flyorov's team began studying the interactions of multiply charged ions with atomic nuclei they had no clear idea of what it would lead to. They decided to take as their starting point the hypothesis of the formation of compound nuclei advanced by Bohr in 1936. He, you will remember, suggested that nuclei colliding with sufficient energy almost instantaneously (the collision taking around 10^{-21} second) formed a compound system in which all the excitation energy, according to the liquid drop model, is more or less uniformly distributed among all the nucleons. The excitation is then eliminated by ejecting neutrons. But why neutrons? Because the Coulomb barrier rather hampers the ejection of charged particles. The formation cross-section* of a compound nucleus depends on the energy of the impinging particle as well as on its type; but the way excitation is got rid of in Bohr's theory does not depend on how the nucleus is formed.

A compound nucleus has a very long life (in nuclear terms), longer than an ordinary nucleus, and has time to 'forget' its origin. Once formed, it behaves quite independently; the way it distintegrates and the length of its life have no correlation with its initial state, and its behaviour may differ very much from that of its parent-nuclei. Calculations made later by theorists who based themselves on Bohr's theory and introduced corrections for nuclear-cascade transfer of nucleons during direct or grazing collisions, agreed well with experiments in bombarding targets with protons, alpha particles, and deuterons.

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* Formation cross-section is a concept analogous to the cross-section of a current conductor, or a stream of fluid in which certain phenomena are to be studied. The size of the reaction cross-section is proportional to its probability.

But now it was a question of heavy ions. Would a compound nucleus always be formed? Would the theory hold for heavy ions? Only experiment could give the answer.

At the Kurchatov Institute Flyorov's assistant, A.S. Karamian, and his young colleagues were already studying the reactions from bombarding gold and vanadium with carbon ions. They had chosen these elements for two reasons. (1) They expected a compound nucleus of zinc-64 to be formed. Its 'behaviour' had been described in the literature and it would be possible to compare the findings and bring out the special features of reactions with heavy ions. (2) Natural vanadium consists almost exclusively of one isotope, vanadium-51, which would make it easier to interpret the results.

Ordinary nickel or aluminium foil was put into a vacuum, in which either gold or vanadium was evaporated to deposit a layer 0.2 milligram per square centimetre thick on its surface. A pile of the coated foil was used as the target. The data obtained as a result of the experiments were typical of the formation reactions of compound nuclei, de-excitation being accompanied by rival processes with the emission of two, three, or even four neutrons, depending on the excitation energy.

It was thus established that when heavy ions and a nucleus interacted the reaction did proceed in accordance with Bohr's theory, though with certain deviations, to wit that the number of emitted neutrons did not always increase with a rise in energy; even at an excitation energy of 60 MeV, when the compound nucleus was a strongly heated, 'boiling' bundle of nuclear matter, occasionally only two neutrons were expelled.

If we drop boiling water onto a red-hot frying pan,

it does not spread out but takes the form of a flattened drop that runs rapidly around the pan without boiling away. The drop gradually evaporates, but more slowly than if it had boiled.

So it was here. It turned out that the neutrons carried off too much of the excitation energy. The eminent physicist V. F. Weisskopf suggested that some kind of local heating was the reason. Sometimes, when a multiply charged ion collides with a nucleus, there is no time for the excitation energy to be spread over the whole nucleus, which causes strong heating in one spot, so that the escaping neutrons gain very high energy. Thus the effect of multiply charged ions is to give neutron a much higher energy than protons would.

The compound nucleus resulting from fusion of a multiply charged ion and a nucleus of the target is not only strongly excited but has high angular momentum, which is partly carried off by the escaping neutrons. But then their energy would have to be greater than that corresponding to the temperature of the nucleus. The Soviet theoretical physicist V. M. Strutinsky calculated that the neutrons could not wholly carry off all the great angular momentum induced by the multiply charged ion. What happens to it is still not clear. It may be that the nucleus emits a cascade of soft gamma-quanta, or perhaps that the great angular momentum reduces the barrier to fission, and the nucleus breaks up.

To be exact the importance of the research carried out since 1956 has in general not been that it provided answers to the questions that had been raised but that the questions had been posed, particularly those that needed close study. For in science it is just as important to pose a problem correctly as to obtain results, the more so when it is impossible to interpret the latter properly.

Systematic experimental research into the probability of a compound nucleus being formed in reactions between complex nuclei is not yet finished. There is still no clear, unambiguous answer why the life of a compound nucleus is sometimes vast (on a nuclear scale), whereas at other times it is quite short. The lifetime of many compound nuclei has already been established and found not to depend on that of their parent-nuclei, but it is still not wholly clear why a certain type of decay predominates in the competition to carry off excess excitation. Can any means of getting rid of the energy be imposed on the nucleus? Is it even possible in principle? These questions are still difficult to answer, but the conditions are known, and have been experimentally established for certain nuclei, when they tend to emit neutrons or to get rid of the energy by a cascade of gamma-quanta. And that is of great significance since fusion of nuclei is the principal way of creating superheavy atoms.

All these problems are of burning interest and it is difficult to exaggerate their importance. So we shall consider in detail how they were tackled in the Laboratory of Nuclear Reactions of the Joint Institute of Nuclear Research. But before we do so let us once more recall Dmitry Mendeleev.

PLAYING NUCLEAR PATIENCE

Mendeleev's remark about the need to observe certain guiding rules when picking mushrooms is also true for many other activities; and for understanding Nature's hidden secrets it is a thousand times applicable.

In order to create a new nucleus, or even to study one obtained, it is not sufficient to have the most perfect tools; the most powerful cyclotron, multiply charged

ions, or the most sensitive instruments will be of no use if one does not at least have a vague idea of what the thing one wants to obtain should be like. In creating matter it is necessary to have some idea of the rules of its life, otherwise it will be still-born.

It is obvious when you think about it.

The essence of the Periodic Table is that the way the elements (i.e. atoms) are arranged, horizontally and vertically, determines their principal physical and chemical properties, which obey clear and exact laws, and enables us even to predict the properties of elements quite unknown. If a similar orderly system, embracing the properties of absolutely all isotopes were created in the field of atomic nuclei, the work of the creators of new elements would be much easier, as they would have almost all the recipes (or at least rough notes of them).

Unfortunately, the known laws that govern one or other of the isotopes of any element are far from as clear and exact as for atoms; and the lives and types of decay of isotopes (and it is difficult to choose the best method of research without knowing them) often surprise theorists and experimenters or lead them up the garden path. But that is by no means evidence of lack of zeal on their part.

Mendeleev was concerned with the fifty or so unsystematized chemical elements then known. It is said that, in trying to understand their relationship, he time and again 'played patience' with the cards bearing their names and atomic numbers. But, as he joked later, he saw the famous Table in his sleep.

Now there are 104 elements in the Table, and each of them has several heavy and light isotopes. The total number found in nature or synthesized is around 1600, and around 5000 are thought to exist. It is not so simple to play patience with a 'pack' that thick.

Ernest Rutherford, the discoverer of the atomic nucleus, said at the beginning of the century that the periodic system of nuclei would be much more complicated than that of atoms, and that a curved surface would probably be needed to illustrate it, rather than a flat one as with the periodic system of chemical elements.

His words proved prophetic. For thirty years the history of nuclear physics has abounded in attempts to get the game of nuclear patience to come out, but none of the systems suggested has been accepted, and the opinion even hardened that the task was insoluble.

But, for all that, some progress had been made.

Though there were still many blank spots on the chart of isotopes, something very important had already been cleared up and was even being used for practical purposes. Isotopes with an even number of particles in their nuclei are known to be very stable; suffice it to recall the magic numbers. Odd nuclei, which disintegrate rapidly on the contrary are extremely unstable, especially odd-odd ones; those with an odd number of protons (the number of protons is equal to the element's atomic number Z) and an odd number of neutrons ($N=A-Z$).

A stable atomic nucleus is a very steady system; to eject a proton or a neutron from it, an energy (known as its binding energy) of several million electron-volts is needed. The stability of a nucleus results from the operation of powerful nuclear forces of attraction. But the degree of nuclear attraction essentially depends, obviously, on the neutron-proton ratio N/Z. The most stable N/Z ratio (in the case of light nuclei) is unity.

In Flyorov's laboratory they have drawn up a 'stability chart' showing the limits of the nuclei that

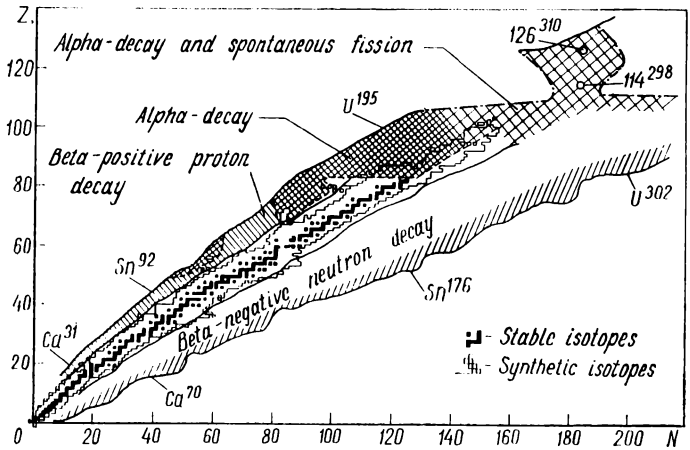

Chart of the stability of atomic nuclei

are most likely to exist. Each point on the chart corresponds to an isotope of a particular element with a certain mass. The number of protons in the isotope is plotted against the vertical axis, and the number of neutrons along the horizontal one.

At the lower left corner of the chart the N/Z ratio is unity and, at the upper right corner, where the stable nuclei of heavy elements are shown, it is approximately 1.5. A deviation from these values indicates a lowering of stability. Let us take the isotopes of hydrogen as an illustration. The isotope with one proton H_1^1 is ordinary hydrogen, which is a stable and very widely distributed formation. Hydrogen with one proton and one neutron H_1^2, or deuterium, is also stable.

Tritium, H_1^3, that is hydrogen with one proton and

two neutrons, has an N/Z ratio of 2:1. This heavy isotope is radioactive and disintegrates (its half-life being 12 years).

Just as in the table of the elements there can be chemically active and inactive elements, so on the chart of isotopes there are regions where all the elements and their nuclei are more or less stable. The boundary of stability for heavy nuclei lies around lead and bismuth. Then comes a region of highly unstable radioactive nuclei that disintegrate rapidly, the boundaries of which define, in fact, the total number of isotopes that can be obtained. As can be seen from the chart, this number is much greater than what we already know. But that is not all. The boundaries indicate the directions that are of interest for research and the types of disintegration typical of a particular direction. Among the isotopes that can exist but are not yet known there are many with interesting properties.

The upper limit of the field of isotopes is determined by a proton binding energy close to zero, and the lower limit by a neutron binding energy of zero. The regions most tempting for researchers are in the boundary zones. In the left-hand part of the table are nuclei with an abnormally small number of neutrons (i.e. neutron-deficient ones). What are their properties and peculiarities? In the right-hand part are nuclei with an excess of neutrons and a deficiency of protons, for which intensive transformations of the nucleons ($p \leftrightarrows n$) and all the types of beta-negative decay are characteristic.

At the top of the chart is a region of superheavy nuclei that may possess most unexpected properties. The heavier the nucleus, the more it is liable to break into fragments, so that their predominant type of decay is spontaneous fission.

The further a nucleus is from the line of stability,

the shorter its half-life, and the less stable it is. Nuclei cannot exist beyond the limits of the field of isotopes.

This chart of nuclear stability based on the proton/neutron ratio can serve us as a guide for our journey through the world of atomic nuclei. With it we can clearly trace the trends of the research that are considered basic at Dubna.

Research into boundary conditions always, as a rule, presents special interest. An unexpected world opens up before scientists in the region of ultralow temperatures, ultrahigh pressures, ultrahigh temperatures (when matter becomes ionized gas or plasma), and superhigh energies involving the interaction of elementary particles. Humanity is quite rapidly feeling the results of penetration of this world in the form of new material wealth.

The extreme proton/neutron ratio is realized in the atomic nuclei lying very close to the boundary of their existence. For atomic nuclei boundary conditions in nucleon ratio (proton-neutron) lie at the limits of their possible existence; and in investigating them physicists obtain important results and interesting information on the properties of nuclear matter.

A NEW TYPE OF RADIOACTIVITY

Let us continue our journey, consulting our chart now and again.

Do you remember Vitaly Karnaukhov, the resolute young fellow who came to Flyorov almost before his diploma was dry, and immediately found himself at the centre of events? He is now an experienced experimenter leading a group in the Dubna Laboratory of Nuclear Reactions that is blazing new paths and filling in the gaps in the isotope chart where N/Z

is less than unity and where (to the left of the stability line) neutron-deficient nuclei are to be found. How do these nuclei behave? That remained a puzzle for some time.

It all began in Moscow back in the autumn of 1954, when dreams of powerful ion-projectiles began to take real shape. During those exhausting and strenuous days, when nothing was yet clear but many things were already beginning to stand out, the active and indefatigable Flyorov, constantly bubbling with ideas, kept his little group in a tension of continuous search.

Once, coming straight back to the laboratory late at night from an important conference at the Academy of Sciences, he began to talk nonchalantly from the doorway, while still in his overcoat, of an idea that had struck him during a private conversation—the possibility of there being special nuclei that were proton emitters. Then, passing on to other matters, he threw out his usual favourite remark almost by the way:

'Think it over, Vitaly.'

It worked like a virus. Once it got into a man's mind it gave him no peace, and gradually took possession of him, little by little.

Vitaly thought it over. At first incidentally, in odd spare moments between his hectic work and his dreams of future experiments to synthesize elements 102, 103, and 105. One day young Prof. Goldansky, a nuclear chemist, bubbling with ideas like Flyorov and apt to be carried away by them, came to the Institute. He and Karnaukhov began talking quite by chance. Goldansky proved not only to be marvellously knowledgeable about the problem but to be working on his own original hypothesis of proton emitters.

But what is this proton radioactivity? What are the conditions needed for it? This is the point to talk about

radioactivity in greater detail. First of all, let us define more precisely what we mean by it.

Radioactivity used to mean any spontaneous nuclear disintegration involving the emission either of alpha particles or of electrons, independent of how long it lasted. Then, as radioactive nuclei began to be obtained in various nuclear reactions, it was naturally asked how long a compound nucleus, for example, would live before the 'first act'—its formation—could be considered completed, and when the 'second act'—radioactive disintegration—began. It was established that the two stages of a nuclear reaction (the first, when the bombarding particle a and the target nucleus A fused to form a single excited compound nucleus K; and the second, when nucleus K disintegrated into particles b and a nucleus B) could be considered separate, if the life of nucleus B considerably exceeded the maximum duration of nucleus K (10^{-14}-10^{-13} second). Otherwise the characteristics of the decay of nucleus B would depend on the properties of nucleus K.

Study of radioactivity had also enlarged the 'range' of its basic types. Instead of the three elementary radioactive processes known at the middle of the century, the nuclear 'ABC' now numbered five: alpha decay; three types of beta decay (emission of electrons or positrons or capture of an orbital electron); gamma radiation; the spontaneous division of a nucleus into two fragments (fission); and proton emission.

Only alpha decay and one of the types of beta decay (emission of an electron) have been observed in natural radioactive isotopes. All the other transformations have been discovered in synthesized isotopes.

Alpha decay, or the emission of alpha particles (helium nuclei), was discovered by Rutherford in 1898. With this type of decay the charge of the nucleus diminishes by two units and its mass by four units,

because it simultaneously loses two protons and two neutrons.

Beta decay with the emission of an electron was also discovered by Rutherford in 1898, while investigating the radioactivity of uranium salts.

It became clear much later that, in this type of decay, a neutron is changed into a proton within the nucleus with the emission of an electron and an antineutrino, which explains why the decay is accompanied with the escape of fast electrons. The mass of the nucleus does not change but the charge increases by one unit.

Beta decay with the emission of positrons (positively charged electrons) was first noted by the Joliot-Curies during the decay of a synthesized nucleus. In beta-positive decay a proton is converted into a neutron with the ejection of a positron and a neutrino. By emitting a positron the nucleus reduces its charge by one unit.

Beta decay with the capture of an electron was discovered in 1937 by that brilliant experimenter and Nobel Prize winner, Luis Alvarez.

Sometimes the nucleus captures an electron from the shell nearest to it, and then one of its protons, having emitted a neutrino, is transformed into a neutron. On one occasion a nucleus may be transformed by electron capture, and on another occasion undergo positron decay.

If we consider the scheme of beta decay:

$$n \rightarrow p + e^- + \tilde{\nu};\ p \rightarrow n + e^+ + \nu;\ \text{and}\ p + e^- \rightarrow n + \nu$$

we can easily see that all the nucleons can be transformed into each other by transposing particles from the left side to the right side, replacing one particle of a pair by its antiparticle: an electron by a positron, a neutrino (υ) by an antineutrino ($\tilde{\upsilon}$). For that reason

β^- and β^+ decay and electron capture are treated as varieties of a single elementary radioactive process—beta decay.

Gamma decay was discovered in France by P. Villard in 1901. In this type of decay the nucleus emits gamma-quanta, i.e. electromagnetic radiation of short wavelength, and no transmutation of elements occurs. But gamma-quanta may sometimes be emitted by nuclei in isomeric states.

Spontaneous fission of heavy nuclei was discovered in 1940 by Petrzhak and Flyorov. Its possibility had been suggested by Niels Bohr in the late Thirties (in 1939). In this radioactive transformation the nucleus spontaneously breaks down into two fragments of comparable mass.

Proton radioactivity. The possibility of such decay (with the emission of protons) had already been posed by the Soviet physicists A.B. Migdal, B.T. Heiligman and B.S. Jelepov in the late Forties. They had reached the conclusion that it could quite probably be detected experimentally. Jelepov had even indicated the region where it could be anticipated.

Developing this idea, Goldansky suggested in 1960 that two-proton radioactivity (i.e. emission of two protons) should be observed with nuclei of the even elements (up to calcium) and gave a detailed description of the phenomenon. To substantiate it he drew a witty analogy with the pairing of electrons possessing contrary spin*. Although electrons have identical negative charges, it is known that in certain conditions (in particular with a sharp drop in temperature) they

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* Spin is a term denoting the intrinsic angular momentum of microparticles, which has a particular quantum character and is independent of the orbital motion of the particle. It can be roughly illustrated by picturing the particle as a revolving body.

form pairs, releasing energy in doing so. Electron pairing is responsible for such phenomena as the chemical bond in molecules, and superconductivity (when a metal loses resistance to the passage of an electric current). In certain conditions, it would seem, the protons in the nucleus can also pair. Occasionally it proves more advantageous for a nucleus to eject two protons at once than to tear them apart.

Why should the nucleus prefer to decay in one way rather than another? What are the laws and mechanisms governing radioactive decay?

The answers are still sought by purely statistical ways. As we know, the laws concerned were then only being groped after. But thanks to a scheme suggested by I.P. Selivanov we can assess certain features of the various types of beta decay.

It has been established that 46 per cent (almost half!) of naturally occurring or synthetic elements prefer beta-negative decay (electron emission).

The ejection of a positron, another type of beta radioactivity, has been observed in only 11 per cent of known nuclei, and these are all synthetic ones practically unknown in nature.

About a quarter of all radioactive nuclei are transmuted by means of electron capture.

Occasionally a 'radioactive fork' is observed—the nucleus can decay in one of various ways. Why? Simply because, in striving for stability, a nucleus with a preponderance of protons, i.e. in which N/Z is greater than unity, will either reduce the numerator of the fraction or increase the denominator; this means that the neutrons will be transformed into protons, and so there will be beta decay. Hence, beta-negative decay is typical of radioactive isotopes with a surplus of neutrons, i.e. of the heavy isotopes of various elements.

Around 10 per cent of all known isotopes emit alpha particles. This is the type of decay best studied. There are around 160 alpha-active isotopes, primarily those with Z higher than 80, i.e. isotopes of heavy elements. It can also occur in lighter elements (for instance in samarium and other rare-earth elements) owing to certain features of their nuclear structure.

Finally, for very heavy nuclei, in particular those of transuranic elements, the predominant mode of decay is spontaneous fission. The charge of the nucleus is so high that it requires less energy for it to disintegrate of itself without external interference. Among the naturally occurring radioactive nuclei, those of thorium-230, thorium-232, uranium-234, uranium-235, and uranium-238 undergo spontaneous fission. (Spontaneous fission has been detected in around 30 isotopes of the transuranic elements, and in the heaviest elements it occasionally predominantes over alpha decay.)

And then there is the ejection of protons. That, clearly, can only occur in nuclei experiencing a very acute shortage of neutrons; otherwise they would prefer some type of beta decay. When and under what conditions will such a shortage occur, and what sets its limits?

So, Karnaukhov thought and thought, and the more he thought the keener he became on the idea. He 'infected' Nicholas Tarantin, and the two of them would set down on paper the way the future experiment should go, trying to predict nuclei 'suspected' of proton radioactivity. Soon they were consulting Flyorov and comrades about one version or another. Flyorov believed heavy ions could be used to produce unstable neutron-deficient nuclei. Karnaukhov was deciding on the most advantageous reactions and was

so absorbed in it that it seemed a nuisance to him to have to do anything else.

The idea of the search for proton emitters was maturing like a novel—to begin with an outline, a vague general plot, then the details, and finally complete harmony.

At long last the most powerful 'wonder gun', shooting charged ions, was at their disposal. They no longer worked in small basement rooms but had moved to a beautifully equipped laboratory, in fact, a real modern institute with roomy offices, light laboratories, and their own machine shop.

But, as usually happens, everything proved dozens of times more complicated than it had seemed in theory, and it took them another three years of strenuous effort in order finally to set up the experiments.

Karnaukhov's group—Vladimir Subbotin, a radio engineer, Gurgen Ter-Akopian, a physicist, Nicholas Danilov, the laboratory assistant, and Leonid Petrov, only just graduated—themselves assembled and adjusted the rather complicated equipment they had designed.

The complication was that, by all accounts, proton emitters should be very short-lived; so the classical way of studying new isotopes after chemical isolation was quite inapplicable. Their instrument had not only to register radioactive decay but also to determine precisely what kind of decay the isotope preferred. It had also to define and give unambiguous evidence of what kind of particle had escaped from the nucleus (electron, alpha particle, or proton); for to cover the shortage of neutrons, the 'deficient' nucleus may choose any mode of decay.

In order to determine exactly what particle has escaped, scientists make use of the capacity of particles of different velocities to be decelerated in a substance.

By simultaneously measuring a particle's energy and rate of deceleration, it is possible to identify it very accurately.

The instrument had to be mounted as close to the cyclotron beam as possible, i.e. it had to operate in a very strong magnetic field, in high vacuum, and near electrodes that had been given a high-frequency voltage of 300 kilovolts!

The 'probe' was constructed first. It looked like a stylized metal wolf: the square metal 'head' contained all the instruments that were to be inserted into the 'muzzle' of the cyclotron. Any other recording instruments needed were put in the elongated 'body'. The 'legs' had wheels for convenience in shifting it. The 'head' was protected by a shield and had a 'telescope' mounted on it during the first experiments, consisting of two gas counters to record nuclear decay. A particle emerging from the nucleus during decay would pass through the two counters; the first would measure its rate of deceleration, and the second its energy. The signals from them were to be processed by electronic equipment.

Karnaukhov and Ter-Akopian started their experiments early in the morning on Saturday, 30 June 1962. Mounted in the path of the beam of accelerated neon-20 ions in the cyclotron was a target of thin sheets of nickel foil.

'Attention! Cyclotron on!'—warned a flashing notice. In a room away from where the instruments were, the two men pressed close to the screens and watched the tape of the recorder.

Under bombardment with accelerated neon ions, the nucleus of nickel should capture an ion and form a heated compound nucleus. On cooling it should emit neutrons and gamma-quanta. Eventually, there would be an excess of protons; their binding energy would

be greatly reduced, and the nucleus would be forced to emit a proton in order to find a stable state.

But—the expected effect was not observed. Or rather it was, but there was no firm assurance that everything was really as supposed. The number of beta-active nuclei formed during the reaction was a million times greater than that of proton emitters. The proton 'shot' had taken place on a background of countless electron 'machine-gun' bursts.

Karnaukhov and Ter-Akopian spent the whole of Saturday night, and all Sunday, Monday, and Tuesday, trying to find how to eliminate the electrons and their jamming background. Suddenly it dawned on Gurgen that the shielding window in the cover of the instrument should be shifted so as to become inaccessible to electrons.

They experimented again. At last protons, real protons, as they say, poured through—but 'poured', of course, on a nuclear scale. In ordinary terms it was more like looking for a needle in a haystack. But call it what you will, a new kind of radioactivity had been discovered. And though success was rather dragged out in time, it was a triumph!

The Learned Council of the Joint Institute reported the results of the experiment to the third international conference on reactions between compound nuclei held in the United States in April 1963. Reporters from Moscow papers, radio, and television rushed to Dubna to interview Karnaukhov. Friends hastened to congratulate him. But he, it must be said, was rejoicing least of all. To be frank, he was simply furious. He hated reporters. Though generally noted for a quite peaceful disposition, he was if anything stubborn and not the least inclined to show off. It was simply, as he then admitted, that what he needed at that moment of triumph was not the beating of drums but a busi-

ness-like, human, heart-to-heart talk; and the naive questions of the uninitiated simply irritated him.

Why? There were two reasons. For one thing, that was his character; and for another, he was too young to have learned indulgence. But there were other reasons, too. First of all, he was impatient to move forward—it had become clear that much was not known and that in fact they knew very little—neither the life of proton-radioactive nuclei nor the reactions that produced them and the mechanisms of these reactions. He wanted to think about new experiments and discuss them, instead of endlessly chewing over old ones. And second (or perhaps it was first), he suddenly realized that thinking about an experiment and working it out was incomparably more attractive than the most brilliant results: 'When you are carrying out an experiment you know exactly what you have to do now and what later, and what will come of it—it is usually humdrum routine. But when you are mulling things over you can mentally grasp the whole complex at once—the initial difficulties, and what won't fit in later, and the whole fullness of the final happiness of a new discovery.'

In brief, they began preparing new experiments immediately. It took the designers, mechanics, and electronics men nearly another six months to alter and adjust the equipment.

The improved instrument recorded proton decay. It was also mounted in the vacuum chamber of the cyclotron shielded by a special screen. The beam of ions struck the target and induced nuclear reactions in it. Around ten million nuclear collisions occurred every second but only ten of them could yield the necessary isotope. The nuclei synthesized were knocked out of the target and caught by a rapidly revolving disk that passed them to the charged-particle spectro-

meter, which also determined their decay energy and what kind of particles they were. But while a particle's energy was now measured by a semiconductor detector, its rate of deceleration was recorded in a gas as usual. The point was that the rate of deceleration for a given energy is the higher, the greater the mass of the particle, so that the pulses produced by protons in a gas counter are weaker than those produced by alpha particles but stronger than those resulting from electrons.

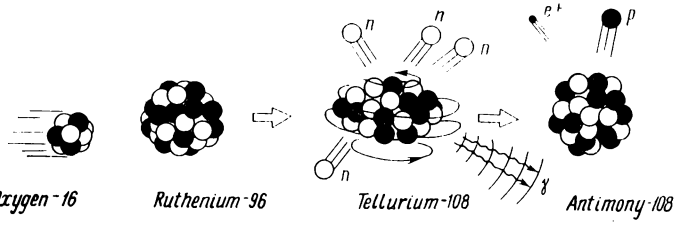
The sensitivity of the electronic equipment used for analysis was raised in order reliably to distinguish proton emitters on a background of beta and gamma radiation millions of times stronger.

By 1964 the Dubna physicists had synthesized several nuclei—proton emitters with energies between 2 MeV and 5 MeV and half-lives of 0.09, 23.3, and 30 seconds. These proton-emitter isotopes were located in various parts of the system of elements. The first two were isotopes of neon and magnesium, and the last two of tellurium and antimony.

The mechanism of the reactions by which proton-radioactive nuclei were produced was clarified. It turned out that there were at least two mechanisms. When ruthenium, for example, was bombarded with oxygen ions accelerated to 100 MeV, there was a certain probability that the two nuclei (ruthenium-96 and oxygen-16) might fuse on collision. The compound nucleus would cool down like a rapidly rotating heated drop of liquid, boiling out neutrons and gamma-quanta. The result would be a radioactive nucleus with an abnormally high neutron deficiency:

$$\text{ruthenium-96} + \text{oxygen-16} \rightarrow \text{tellurium-112} \rightarrow \text{tellurium-108} + 4n + \gamma;$$

$$\text{tellurium-108} \xrightarrow{\beta} \text{antimony-108} \xrightarrow{p}$$



How proton radioactivity can be pictured

The antimony-108 nucleus is 13 neutrons lighter than the lightest stable isotope of antimony (antimony-12) and will emit protons.

The same sort of thing happened when an accelerated neon-20 ion hit a nucleus of nickel. They fused, and the heated compound nucleus cooled down almost instantaneously, emitting nucleons and yielding light isotopes lying somewhere between selenium and strontium.

That reaction, however, was not the sole one between the nuclei of ruthenium and oxygen or neon and nickel, and more than that, it was the least probable one.

Apart from reactions in which the two interacting nuclei fused, there were grazing reactions. Nuclei transfer groups of nucleons to each other on coming into contact, and as a result produce proton emitters with half-lives of 0.8 and 0.09 second. In this case, when nuclei of neon and nickel, for example, graze, nucleons are transferred from one to the other producing an isotope nucleus only slightly different from the original one (e.g. the neon ion), but deficient in neutrons.

This second type of proton decay is sometimes called delayed proton radioactivity. It is a two-stage process. In the first stage, the nucleus supersaturated with protons undergoes beta decay, emitting a positron and capturing an electron. One of the protons is thus transformed into a neutron. Part of the decay energy remains in the daughter nucleus and is transferred to the proton with the weakest binding energy. This proton is then in such a state that only the Coulomb barrier retains it in the nucleus. Or again, the proton will pass quite rapidly through the barrier by the tunneling effect and escape. The time taken is extremely short, but considerable on the nuclear scale. A nuclear unit of time, remember, is the time it takes a particle to pass through the nucleus (3×10^{-22} second), or the time of one 'revolution' of a proton within a nucleus. (Some physicists figuratively call this interval of time a 'nuclear year'.) The first stage (positron decay) occurs much more slowly than the second; therefore we can observe proton radiation of an intensity that decreases with time in accordance with the half-life characteristic of a beta transition. Heavy nuclei have a similar mechanism of decay when emitting 'long-range' alpha particles.

Proton radioactivity was independently discovered in 1963 at McGill University in Montreal by the Canadian physicists R. E. Bell, R. Barton and H. G. McPherson. They studied the second type of reaction—the two-stage process: delayed protons with energies between 2 and 5 MeV emitted by nuclei that are the reaction products resulting from bombardment of aluminium, magnesium, fluorine, sodium, and oxygen with protons of 97 MeV in the external beam of McGill's cyclotron. (It is of interest, incidentally, that it was there, at McGill University, that Rutherford discovered alpha and beta radioactivity.)

By late 1964 nine proton-emitting isotopes had been synthesized by the efforts of Soviet, Canadian, and American physicists. And questions naturally arose. Is this a common phenomenon? Or is it, perhaps, characteristic of only a few exotic nuclei? Is there any sense in studying it extensively? Can it contribute new information about the atomic nucleus?

The answers were given in the papers of the international conference on the physics of heavy ions held in Dubna in 1966.

Existing knowledge of the properties of atomic nuclei was sufficient to predict the existence of isotopes capable of proton decay. The predictions were not perfect, of course, and experiments would certainly make them more accurate, but they reflected the general picture of their occurrence.

The sphere of proton decay extends over practically the whole system of elements and is as common as alpha decay, the 'veteran' of radioactivity. It is a regular property of isotopes with an excess of protons. Proton emission is not, of course, the only way these nuclei decay, and alpha decay is a close competitor, but not in the region of nuclei lighter than tin ($Z = 50$). Beyond tin, however, the role of alpha decay becomes more conspicuous, and is particularly active near nuclear shells corresponding to the magic numbers of 50 and 82 for neutrons, and 82 for protons. Alpha decay then 'draws even' with proton decay. In the region of heavy nuclei it reigns supreme; but there, too, there is hope of observing proton emission, though it will require more sophisticated and accurate equipment than that so far employed.

The properties of nuclei are not the same over the whole region of proton decay because of the fact that the degree of proton instability of a nucleus increases as the number of neutrons gradually decreases. First

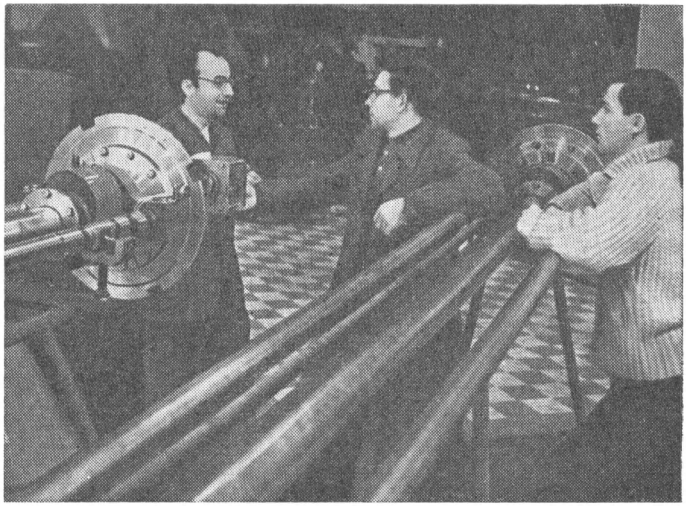
come isotopes that undergo proton decay only after a certain amount of 'heating up'. The main role here is played by the two-stage mechanism, or delayed proton radioactivity. As we advance further into the 'realm' of proton decay proton emission becomes likely without additional 'heating' of the nucleus, which will happen as we cross the red line corresponding to zero binding energy.

Greater neutron deficiency still leads to such instability of proton emission as to preclude any practical possibility of recording decay, and gives rise to a 'left' boundary in the region of proton-radioactive nuclei.

Strange as it may seem, proton decay differs essentially in isotopes with odd and even numbers of protons. The difference is linked with the action of the 'pairing' forces by which an even proton is more firmly bound to the nucleus than an odd one. In outlining the contours of the region of proton decay we have not, for simplicity's sake, drawn the line between odd and even nuclei.

The pairing effect may be the reason for the radioactive decay of even nuclei with emission of two protons at a time, theoretically predicted by Goldansky. Two-proton decay does not seem to be as common as single-proton decay. The region where it occurs is the chain of even-Z nuclei running along the line of zero proton binding energy. For nuclei with more than 34 protons, two-proton decay will be greatly hampered by the competing process of positron emission.

That is how the first steps were taken into a new region of nuclei capable of a hitherto unknown mode of radioactive transformation. Karnaukhov affirms, with good reason, that practically any nucleus can be produced, 'suspect' as regards radioactive emission of protons. The most effective and universal 'tools' for



V. A. Karnaukhov (centre) with colleagues at Dubna

synthesizing them are the nuclear reactions induced by multiply charged ions. Beams of light, charged particles—protons, deuterons, and alpha particles—can also be employed. These 'tools', however, can only be effective with elements with a charge less than 30.

'Just now,' Karnaukhov said, 'we are only investigating the phenomenon itself. But I'm sure that it will soon become a means for studying nuclei in a completely unstudied field—nuclei supersaturated with protons. We've good grounds for hoping that such research will yield new, possibly unexpected information.'

The Canadian group fully shared his opinion. Professor Bell told reporters that we could not expect

immediate practical application of proton radioactivity, mainly because the life of proton sources is only a few seconds long. But it was indispensable for studying nuclear structure. Its great advantage was that the proton spectrum consisted of discrete lines, unlike the continuous beta spectrum, which made it very distinct.

What can we learn from proton radioactivity? Above all it enables the contours of the region of proton activity in nuclei to be accurately determined, and provides information on the location of the line of zero binding energy. What we know so far comes from calculations based on the properties of nuclear interaction, as established by study of near-stable isotopes. Experience will show how far it is applicable to isotopes that are far from stable.

It is very important to measure the intrinsic time of proton escape from the nucleus experimentally. Simultaneous determination of this time and the decay energy will provide a method for measuring the size of proton-radioactive nuclei, since the three characteristics of a nucleus (its energy, life, and radius) are inter-related and the relationship has been precisely calculated theoretically. So far only the sizes of stable and alpha-radioactive nuclei have been determined. Proton emitters form a new class of nuclei, whose radii will be measured experimentally. But the job is far from simple, for the proton-radioactive nucleus disintegrates very quickly. But the difference between even-Z and odd-Z isotopes offers favourable opportunities for experiment. In view of the high 'proton' stability of even elements two-stage decay should be quite common, i.e. the emission of a positron and the escape of a proton from either the ground or an excited state. The life of a nucleus undergoing positron decay cannot be shorter than 0.01 second. That delay

in proton decay makes it possible to employ spectrometry even though the intrinsic time of proton decay is extremely short. The time can be determined experimentally by simultaneous recording of a positron and a proton. Available electronic equipment enables intervals as short as 10^{-10} second between pulses to be measured.

In speaking of determining the radius of a proton-radioactive nucleus, we imply, of course, that this is characteristic only of spherical nuclei. But will proton-radioactive nuclei be spherical? Theory predicts that the band of proton-radioactive isotopes will cut across a new region of deformed nuclei, and possibly more than one. What is important is that detailed research into proton decay (accurate measurement of proton energy, study of the angular correlations of positrons and protons, and investigation of the ensuing gamma-quanta) will help us get an idea of the shape of the nucleus and the characteristics of its energy states. And those examples do not exhaust the attractions of proton decay for physicists.

ON WHITE DWARFS AND ON EARTH

Let us now look at the right-hand side of our guide near its right edge. There is another region of unique nuclei with an excess of the 'cementing' stuff—neutrons.

Neutron-rich nuclei are by no means a rarity. They not only undoubtedly exist in nature but apparently play a role of paramount importance in the evolution of stars and the development of the natural nuclear-chemical synthesis of elements.

In current views, stars (which contain the bulk of the matter in the Universe) are still evolving, that is

coming into existence, developing, ageing and dying, and changing from states of lower density of matter to ever higher ones. And this may, incidentally, be a closed, circular cycle.

A newly born, young star or, as astronomers say, protostar, condenses from rarefied gas and, because of gravitational pull, begins to emit light. Under the action of gravity the gas contracts, its pressure increases, and it gradually begins to heat up. This amazing process is characteristic of the negative heat capacity of matter, which is impossible in earthly conditions. In fact, the more a star shines and radiates energy, the hotter it becomes. More energy is released by contraction than is expended in luminescence. The surplus energy is provided by gravitational forces. In contracting the star reaches a state in which nuclear forces come into play. At the very high temperatures and densities of its basic substance, hydrogen, light atomic nuclei or proton overcome the Coulomb barrier (repulsion of like charges) and unite, releasing immense energy.

The star becomes a thermonuclear reactor. One source of energy—gravitational contraction—gives way to another, and the star hardly contracts any more. It becomes mature. The red-hot gaseous ball is in a state of hydrodynamic equilibrium; the gravitational forces are counterbalanced by the internal pressure of the gas. But hydrogen burns changing into helium and more and more free protons become bound neutrons. The star shines brightly. In stars like our Sun this process goes on for over ten thousand million years. The Sun itself has lived half that time. For stars bigger than the Sun, this period is hundreds of times shorter, so that most gigantic stars may be coming to the end of their existence.

This period in the life of stars is well known to as-

tronomers and astrophysicists. But what happens afterward is rather foggy.

The hydrogen in the centre of the star has burned up. Now helium is burning and the temperature in the centre is getting higher and higher, and heavier elements are formed, up to iron. The star, which is now poor in nuclear fuel, contracts, thus compensating the radiation from its surface. Because of its heterogeneous chemical composition, its structure is reorganized, its envelope begins to expand and its surface temperature to fall. This is the stage of 'red giants'. Finally, there comes a time when everything burnable has been consumed. The nuclear sources of energy at the core have been exhausted, and the resulting iron nuclei cannot burn.

This is the most mysterious period in the life of stars. A catastrophe may occur; the star may explode at the expense of its residual nuclear fuel and throw off its outer envelope. Or things may end quietly; the envelope gradually effuses into space and the stage of stable equilibrium comes to an end.

Astronomers have observed both processes, but still do not know why one is preferred to the other. To obtain an answer requires such complicated and laborious calculations that they would take scores of years even on computers. In the Soviet Union calculation of their behaviour is under the leadership of Prof. Alla Masevich.

But everything becomes more complicated still when the concluding non-equilibrium stage of stellar catastrophes and disturbances sets in. The finale is twilight and apparently will not be calculable with comparative accuracy for many years to come. All the computers available at present are not enough for it, although interesting hypotheses and proposals have been advanced in recent years on the processes

occurring at this stage, and have been supported by astronomical observations. Among those working on these problems are a group of Soviet physicists headed by Prof. Jacob Zeldovich, member of the USSR Academy of Sciences.

If a star does not explode during its evolution it must remain in the final state. What is that state?

The matter of the star has gradually cooled. Its internal gas pressure has diminished and gravitation again become the decisive factor. The force of gravity contracts it to an incredible density where one cubic centimetre weighs almost 100 tons. This terrific force flattens the electron shells of the atoms, and the electrons gain independence. The behaviour of this electron gas no longer depends on temperature but on quantum effects. So that, even when completely cooled, the stellar gas possesses elasticity and pressure, which in the end counterbalances the force of gravity so that the star stops contracting. A white dwarf develops. Luminous dwarfs, radiating white light, go on cooling for tens of millions of years. And though they are considered cold (since the energy of quantum motion exceeds their thermal energy) their surface temperature is as high as 10 000 degrees. That is the fate that awaits our Sun.

The stability of nuclei in white dwarfs no longer observes the limits of our table, compiled for terrestrial conditions. The boundary of stability shifts toward an ever greater excess of neutrons. Neutron-rich nuclei, which are beta-radioactive on earth, become stable in the interior of a star with degenerated electron gas. Compaction during stellar evolution leads to neutronization, i.e. to the conversion of a higher and higher proportion of protons into neutrons.

Only stars with approximately the mass of our Sun can become white dwarfs. If their mass is double that

of the Sun, the gravitational forces increase greatly during cooling, and the star contracts to the density of an atomic nucleus. One cubic centimetre of their matter could weigh 100 million tons. The elasticity of electron gas cannot resist such forces. Only nuclear particles—protons and neutrons—can counterbalance them, and prevent unrestrained contraction, by what is called baryon repulsion, i.e. the elasticity of nuclear matter. The star will become quite small—about ten kilometres in diameter. Such stars have been called 'neutron' stars since practically all their protons have been converted into neutrons. They are very hot (their surface temperature at the moment of formation reaching tens of millions of degrees) but cool very rapidly. They are luminous for only a thousand years, then their luminosity grows weaker and they become invisible.

With neutronization of the nuclei of stellar matter various neutron-rich nuclei are formed. Their abundance in the star depends on the mean value of the N/Z ratio for this state and on the conditions of thermodynamic equilibrium. At low temperatures nuclei with the binding energy maximum for this ratio will apparently be more abundant. And the last compound nuclei existing in the concluding stage of the life of a star, when it is being neutronized, before its transition to the purely neutron state, will probably be those with the highest N/Z ratio in bound states, i.e. the heaviest isotopes of superheavy elements.

What nuclei could remain in the bound state at the highest N/Z ratio? On Earth the value of this ratio for the heavy elements, we know, should not exceed 1.6. But what about stars? What, in general, is the greatest number of neutrons a proton can hold for the system to remain bound? These are much the same eternal questions as with proton excess. And they are

just as difficult to answer with adequate certainty. Journalists love to talk of science conducting a search. With success? That question at least can be answered in the affirmative, and we can even furnish evidence.

The search for the location of the stability boundary of nuclei in the neutron-rich region began some time ago and has been conducted by many theoreticians.

In 1957 the Canadian physicist, Prof. A. G. W. Cameron, compiled tables of nuclear masses calculated from semi-empirical formulas. They have been widely employed to determine the masses of unknown nuclei, but apparently do not hold for the region of high neutron excess. Cameron himself, in 1959, analysing the formation of transuranic elements during nuclear explosions, suggested that a neutron's binding energy falls more slowly with increase in N/Z ratio than shown in his table. More recently, Cameron and Elkin have proposed two new versions of the table.

Their new calculations were based on a dependence between mass and serial numbers such that a neutron's binding energy is always positive and there is no stability boundary. That is at variance with calculations for a purely neutron gas. The N/Z ratio of neutron stars can certainly be very high, but they are bound by gravitational rather than nuclear forces. The analyses of the energy of purely neutron gas without gravitation, made by theoretical physicists in various countries, including Zeldovich, E. Salpeter, J. Cammell, P. Sodd, L. Simmons, and others, have indicated that its positive energy decreases monotonally as its density falls; and it apparently does not acquire the minimum energy necessary for a drop of liquid to exist.

At any rate, there must be a stability boundary. But where?

It was long held that the record for light nuclei

(e.g. helium) was four neutrons to two protons. It was supposed that a helium isotope with an atomic number of 7, i.e. one consisting of two protons and five neutrons, was obviously unstable. In 1960 Zeldovich and Goldansky, determining the stability boundaries for light nuclei more accurately by taking into account the effect of shells and pairing of nucleons, predicted the existence of several neutron-rich nuclei; in particular, they concluded that there must be a helium with a nucleus containing six neutrons (helium-8). Each proton in the nucleus of this superheavy helium should be held by three neutrons. N/Z would be three!

Fantastic as it may seem, experimenters in many countries immediately began searching for the champion. In 1961, while irradiating nuclear photographic emulsion with very fast protons, the Soviet scientists O. V. Lozhkin and A. A. Rimsky-Korsakov observed among the typical T-shaped tracks of lithium-8 decay tracks left by nuclei of identical mass but lower charge. They suggested that these low density tracks were due to helium-8 and not to lithium-8, and that at the end of the track, before lithium-8 decayed ejecting two alpha particles, the helium-8 apparently decayed to lithium-8. Unfortunately, their arguments did not carry sufficient conviction at that time to be taken as proof of the existence of helium-8. But as turned out later, they were sound.

In 1965, G. Cherni et al. in America produced helium-8 by bombarding magnesium-26 nuclei with alpha particles at an energy of 80 MeV. A magnesium isotope with atomic number 22 was also produced in their experiment. The thermal effect of this nuclear reaction could be judged from the amount of energy released through decay of its products, and that, in turn, allowed the mass of the helium-8 to be calculated. The result obtained proved to agree beautifully with

the value predicted by Goldansky some years before.

$$He^8 \rightarrow Li^8 \rightarrow Be^8 \rightarrow 2He^4$$

A balloon filled with helium-8 would spontaneously double its volume.

Then the Americans S. Wheatstone and T. Thomas actually 'saw' helium-8. They were studying the light products of the spontaneous fission of californium-252 by means of a two-dimensional analyser. Each sort of light nucleus has its own band in the energy spectrum. Apart from well known alpha particles, they registered fission products hitherto unobserved (nuclei of helium-6) and in addition obtained around ten counts in the band corresponding to helium-8.

Helium-8 decay was also observed by an American team of physicists led by A. Posckanser. They produced it by bombarding a target of porous plastic or cotton wool with fast protons of an energy of 2.2 GeV.

They managed to record the beta particles, gamma-quanta, and delayed neutrons that are emitted after beta decay of helium-8. The probability of delayed neutron emission was estimated at 12 per cent, which was in full agreement with the observations made by V. M. Sidorov's group working at the Laboratory of Nuclear Problems in Dubna under V. P. Jelepov, Corresponding Member of the USSR Academy of Sciences, who had directly registered the birth and decay of helium-8 nuclei by irradiating of nuclear photographic emulsion with a flux of negative pi-mesons.

From the size of the mass defect* of helium-8 found, which was also in fair agreement with Goldansky's prediction, it followed that the binding energy of a

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* Mass defect is the difference between the mass of the nucleus as a whole and the sum of the masses of all its constituent particles.

neutron pair in the helium-8 nucleus was 2.1 MeV, and of the four neutrons 3.1 MeV. The binding energy of a neutron pair in the helium-6 nucleus is 0.96 MeV, i.e. it is only half as much as in helium-8! If that tendency persists, one may expect the next neutron pair, completing the p-shell, to have a positive binding energy as well. Hence, an even heavier isotope may exist, helium-10, with a magic number of neutrons (eight) and an N/Z ratio of four. But the estimates of masses available do not confirm a bound state for helium-10. So far the record-holder is helium-8 with an N/Z of three. In any case, the nuclei of its multiples, beryllium-16, carbon-24, and oxygen-32, according to available estimates, are far beyond the stability boundary. The existence of helium-8 is of great interest for research into astrophysical phenomena. In principle, a highly neutronized star can contain a great amount of helium-8. But it is highly 'explosive' and its decay is accompanied with a release of energy around 3 MeV per nucleon, which is approximately four times the energy released through the decay of free neutrons.

So the record-holder among the light nuclei is helium-8. But what about medium nuclei? And heavy ones? And the heaviest?

To get an approximate answer, it is necessary to study a vast number of neutron-rich nuclei, to discover their peculiarities, their preferred reactions, and their mechanism of decay. Once again, the role of heavy ions can hardly be overestimated. A great many nuclei with specific properties, namely, with a considerable excess of protons or neutrons, can be produced in direct, or as we have called them, grazing reactions between a nucleus and heavy ions.

The mechanism of direct reactions is being studied by a big international team at Dubna, headed by Vadim Volkov. It has included, at various periods,

A. G. Artukh, J. Wielczynski, G. F. Gridnev, P. Dezovsky, G. N. Zorin, T. Kwiecynska, E. Ložinsky, Jaromir Maly, L. Pomorski, J. Tiss, L. K. Tarasov.

In studying the general picture of direct nuclear reactions with heavy ions, they succeeded in identifying the most probable types among the vast variety of those occurring, and their mechanisms and features. It proved that the number of nucleons transferred from nucleus to nucleus in reactions between ions and nuclei can be very, very great. Thus the terbium nucleus, when bombarded with neon ions, can strip up to ten nucleons from a bombarding neon nucleus. And when tantalum was bombarded, reactions were recorded in which the target nucleus had lost twenty or more nucleons! Where did the nucleons stripped off disappear to? Were they captured by the bombarding nucleus or did they recoil to exist in a free state?

Their fate was tracked down in special experiments bombarding a thin tantalum target with neon-20 ions, in which long-range ions of the isotopes sodium-22, sodium-24, and magnesium-28 were carefully singled out, corresponding to the capture of a deuteron (one proton plus one neutron) and of a group containing two protons and six neutrons. Comparison of the stripping and capture cross-sections of an identical number of nucleons revealed that a great many of the 'detached' nucleons were transferred from nucleus to nucleus. It is these pick-up reactions that are used to produce isotopes heavily enriched with neutrons.

Another feature, no less interesting, came to light. It turned out that the reaction cross-section during nucleon transfer was closely dependent on the composition of the nucleon group transferred. Let us just recall that physicists take the value of the reaction cross-

section as the formation cross-section of one of the reaction products, that is as a characteristic of the probability of some sort of reaction occurring. If we think of the nucleus as a ball, its radius will be of the order of 10^{-12} centimetre, and the cross-section 10^{-24} square centimetre. When a projectile nucleus strikes such a small area of the target nucleus a nuclear interaction occurs. The probability of its doing so is proportional to the geometric dimensions and energy of the projectile nucleus. Thus, with tantalum, the probability of the transfer of two protons and two neutrons at once is a hundred times greater than the transfer of two protons only, while the probability of three protons and three neutrons being transferred is ten times greater than for three protons and one neutron. A similar dependence has been observed for terbium. It may be that the transfer of several nucleons is more likely within a bound group, groups containing roughly the same number of protons and neutrons having the advantage.

In order to achieve success with reactions yielding various exotic nuclei, it is necessary to have a clear idea both of what occurs in the target nucleus and what happens to the bombarding ion. We now know, for example, that, when thorium, gold, tantalum, and other elements are bombarded with ions of nitrogen or oxygen, not only does the target nucleus pick up a considerable number of nucleons from the bombarding ion but the latter may break up into lighter fractions owing to the grazing interaction.

Volkov's group were engaged on rather routine work. They were not producing new elements or discovering new laws of nature. Journalists did not besiege them, and their pictures were only published in the Laboratory wall-newspaper. But you will often meet their names in major journals, because, without

their humdrum work, it was out of the question to produce new elements or disclose Nature's secrets and the unknown laws prevailing deep in matter.

UNCOMMON PROPERTIES OF COMMON NUCLEI

The telephone rang around two o'clock in the afternoon. It was 6 November 1963, the last working day before the November holidays. Work was finishing and even in the Novosty News Agency only three people remain on duty on holidays 'in case something happens'. I was already about to go home when the phone suddenly rang. It was George Flyorov calling from Dubna:

'Could you come to Dubna?'

Flyorov wouldn't be inviting me for nothing. I knew that quite well. He was more likely to run and hide to dodge journalists. But we were old friends and I could count on mutual confidence and understanding.

I caught the 16.00 train and in three hours was in Dubna. From the station to the laboratory it takes seven minutes, but if you take a short cut across the railway tracks and over a pine-covered knoll you can do it in four.

Work was already finished but they were waiting for me. Victor Druin was also an old friend. Flyorov introduced his assistant Sergei Polikanov, and his young colleague Anatole Pleve, a physicist.

'Well, what's happened?'

'They'll tell you all about it,' Flyorov said, and left.

Polikanov began talking. He was a short, brown-haired man with a round face and gentle manner, very polite and reliable, and very calm. Even too calm, it seemed to me after I learned what had happened.

A surprise was in store for world nuclear science. Serendipity had taken a hand again. And where there is a serendipity surprises are not slow to follow.

No one, of course, would dare to assert that any unexpected and at first incomprehensible discovery will necessarily cause a revolution in science when explained. But every such event undoubtedly calls for earnest attention. More power to those real researchers and real scientists who know how to stop in their successful tracks and exclaim: 'There's something queer here,' and try to find an explanation for it. Thanks to them seeming obstacles and accidental results that are passed over by others with equinimity are suddenly turned into the golden key to long sought treasures.

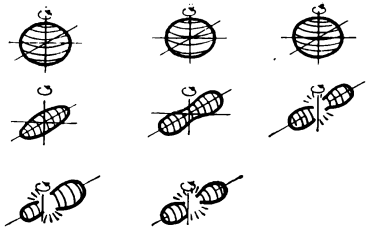
In short, the physicists of Polikanov's team had been looking for element 102 but had found something quite, quite different and were able to pull themselves up and say: 'There's something queer here!'

To appreciate the strangeness of what they saw better, let us turn back a little and remind ourselves of what we know about nuclear fission.

Induced or artificial fission through the effect of neutrons used as bombarding projectiles was discovered by Otto Hahn and Fritz Strassman in 1939. One consequence of their discovery was the atomic bomb, and another the present rapid development of atomic power engineering.

What happens to the atomic nucleus during fission?

Niels Bohr and John Wheeler, who suggested the liquid drop model of the nucleus, believed that it explained the process well. When a droplet is elongated there is a moment when it takes less energy for it to break up into two drops than to remain as a single drop. But it is still not very clear to physicists just why the nuclear forces of repulsion and stabili-



Equilibrium forms of a rotating nucleus

zation are altered and redistributed during changes in the shape of nuclei, as the calculations are extremely complicated.

Theory predicts that the nucleus will divide quite readily when its shape becomes similar to that of a dumb-bell. But that shape does not come about by chance, as can happen during elongation of a drop of water. The energy introduced into the nucleus by a bombarding particle may be absorbed in a practically infinite number of ways, and the additional energy transformed millions of times from one form to another before it is converted into energy of fission—all in as little as 10^{-14} second!

Calculations based on the liquid drop model suggest that the two ends of the elongated nucleus should be equal in size and that the two fission fragments should consequently be of the same mass. But the fission of uranium, for example, does not confirm that: the two fragments are not usually equal, one may be half as big again as the other.

Recent research has indicated that the reason for non-conformity with the liquid drop model lies in the character of the calculations, which assume only two forms of energy in the nucleus—(a) electrostatic energy of the repulsion of particles with like charges,

and (b) energy of nuclear attraction—and disregard the surface energy of the nucleus. And that is quite understandable. At that time nothing was known of the existence of nucleon orbits or shells, and we still, incidentally, do not know much about them.

But that is not the only puzzling thing about nuclear fission. Niels Bohr advanced another important hypothesis suggesting that uranium nuclei might split spontaneously, without energy being introduced from the outside or without bombardment by particles. In certain definite cases it is simply that the tunnel effect, the 'panacea' of quantum mechanics, may develop. In other words, the energy barrier, which is impenetrable in ordinary conditions, suddenly becomes penetrable in terms of quantum mechanics. The reason is possibly that the internal oscillations of the nuclear particles eventually deform the nucleus. For the process of alpha decay (alpha-particle emission) which has been observed thousands of times, is quite inexplicable by the laws of classical physics; only the concept of tunnel effect helped reveal its mechanism. The same phenomenon underlay the mechanism of proton radioactivity. This meant that Bohr's suggestion was well-grounded, but only experiment could be the final judge.

In those years almost every nuclear physics laboratory in the world was studying uranium fission. In Leningrad a special department of nuclear physics under Igor Kurchatov had been set up at the famous Physico-technical Institute, the first major physics research centre in the Soviet Union and headed by a brilliant scientist with a world reputation, Prof. A. F. Joffe, member of the USSR Academy of Sciences.

In this department, and throughout the whole Institute, such was its style, young graduates worked

side by side with eminent established scientists. A. I. Alikhanov, now a member of the Academy of Sciences, was studying radium and its beta-decay products. The late L. A. Artsimovich, formerly Academic Secretary of the Department of General Physics and Astronomy of the USSR Academy of Sciences, was at that time concentrating on the interaction between neutrons and matter. Two young post-graduate students, K. A. Petrzhak and G. N. Flyorov, who had come to Kurchatov while still students, were occupied with various aspects of the fission of atomic nuclei.

Within a year of Fermi's work the first radioactive isotopes of silver (activated by neutron bombardment) with half-lives of 2.2 minutes and 44 seconds had been obtained in the Soviet Union.

In 1935 Igor Kurchatov and his brother Boris, L. V. Mysovsky, and L. I. Rusinov noticed something strange during the bombardment of bromine; unusual, time-anomalous disintegrations were registered. Trying to find an explanation for this, Kurchatov suggested that either bromine had one isotope more than was known, or one and the same nucleus could reach such a state of excitation that its radioactive properties were greatly altered.

The second suggestion proved correct; in fact, artificially created nuclear isomers were first observed in bromine nuclei. Research into isomers continued until 1937, when the first particle accelerator in Europe, a 60-centimetre cyclotron built on the Kurchatov's initiative and under his supervision, began working, at the Leningrad Radium Institute.

The cyclotron gave a big flux of neutrons for bombardment. It was beyond comparison with the weak 150 keV of the Physico-technical Institute on which all the experiments had been carried out until then. Unfortunately, all the counters needed remained at

Phystech, so, having bombarded a specimen at the Radium Institute, they had to run rapidly downstairs to a stand-by car and rush to Phystech to count it.

But every cloud has a silver lining. The technology of the experiment required a few drops of water to be added to the bottle of ethyl bromide and well shaken before counting of disintegrations began. The ride right across Leningrad from the one institute to the other was so bumpy that the specimen was beautifully shaken up.

All attention was focused on studying uranium fission. The uranium for the experiments was brought at a photographic supplier's where it was sold as ordinary intensifier.

They knew very little about the fission process, and even less about chain reactions. And no one then even guessed that there were neutron moderators, graphite and water.

The first thing they found was that uranium-235 absorbed resonance neutrons. Then they decided to check how ordinary metallic uranium would behave, and to try and test Bohr's hypothesis of spontaneous fission. In order to check the counter for the experiment once more, Flyorov got an ampoule of a radioactive preparation from Artsimovich and took it to the Laboratory at night when nobody could get in the way and nothing affect the readings. Just as he was going to fix the brittle ampoule (its walls were less than 50 microns thick) into a holder liberally smeared with warm oil, it slipped and fell to the floor.

'It crashed to the floor—as it seemed to me then,' Flyorov still recalls with a shudder. 'I was afraid to look. If it was broken, the whole room and all the instruments, and not just the instruments, the whole building as well, would be contaminated with radio-

active substances for several weeks, and the experiment postponed indefinitely.

'Imagine! I opened my eyes and there was my precious ampoule, all in one piece, stuck in a crack in the floor! Ugh! I've never been superstitious, but I couldn't help thinking that was an omen of good luck.'

So it was, but that was not the end of the story. They had built the instrument for observing the spontaneous fission of uranium themselves. It was a special ionization chamber with many plates fastened to rods (on the principle of a condenser), so that its volume could be altered.

There were so many plates that the total area of the chamber was over 1000 square centimetres. All the plates had to be given a uniform coating of uranium dioxide. Petrzhak, an excellent artist as well as a physicist, built a contrivance, attaching paint brushes to a bit and a brace. Flyorov turned the handle and Petrzhak applied uranium with a brush.

At last the chamber was assembled and ready. Experiments could only be carried out at night because they wanted to observe the spontaneous fission of uranium without any extraneous effects. So they selected a time when no other instruments were working and the trams were not running. The first pulse was registered at two in the morning, then a second; they looked at the oscillograph, the curve seemed to indicate the presence of fragments. They could not help phoning Kurchatov. He arrived at six. By then the chamber had registered another four fragments.

Furious activity began.

'Kurchatov,' Flyorov relates, 'made us do dozens of "pure" experiments and counter-tests to check and recheck. By day we worked on the cyclotron, and at night counted fragments. Sometimes with the control experiments, we had to run with the specimen from

the room where the indicator was to the one with the control instruments. The corridor of the Institute passed under a staircase and was L-shaped with a sharp corner. Kurchatov ordered a padded pole to be set up at the corner, so we could swing round the turn by one arm. What do you think? We managed to save five seconds!'

'Your chamber's big, there are many alpha particles, and the possibility of overlapping is not excluded,' Kurchatov said.

As a check, radioactive gas was put into the ampoule, and the number of alpha particles increased fivefold. The effect remained the same; the number of events was not altered.

'When the uranium dioxide was being deposited some rough spots, or "islands", may have formed. They would have the effects of charging and discharging,' said Kurchatov.

All the plates were coated with very fine gold leaf, but the effect remained the same.

'But what is the pulse distribution?' Kurchatov asked.

They plotted the curve and found that it was identical for neutron-induced and spontaneous fission.

'If it's spontaneous fission, how will other fissile elements behave?' There was no stopping Kurchatov.

They tried depositing thorium. No effect was observed.

'Cosmic rays can induce uranium fission,' Kurchatov declared then. 'You must exclude the possibility.'

They built a big new ionization chamber of 6000 square centimetres, and to make sure powered it from batteries and not from the mains. Flyorov and Petrzhak were assisted by a newly arrived graduate, V. S. Panasyuk—this last experimental test of the

presence of spontaneous fission had been the theme of his finals' thesis.

The three of them, taking the new chamber with them, left for Moscow. The deep tunnels of the Metro would shelter them from cosmic rays.

They spent a whole day running around for the necessary permission. And only late on a dank November evening did they go down the escalator of the Dynamo Station, then the deepest, balancing their instruments with difficulty. But all the same they had to wait until midnight when the trains stopped running (in braking they sparked and could cause side-effects). For several days they went to the Metro station as if it was their job (from midnight to six in the morning). The effect was constant and invariable. The uranium disintegrated spontaneously.

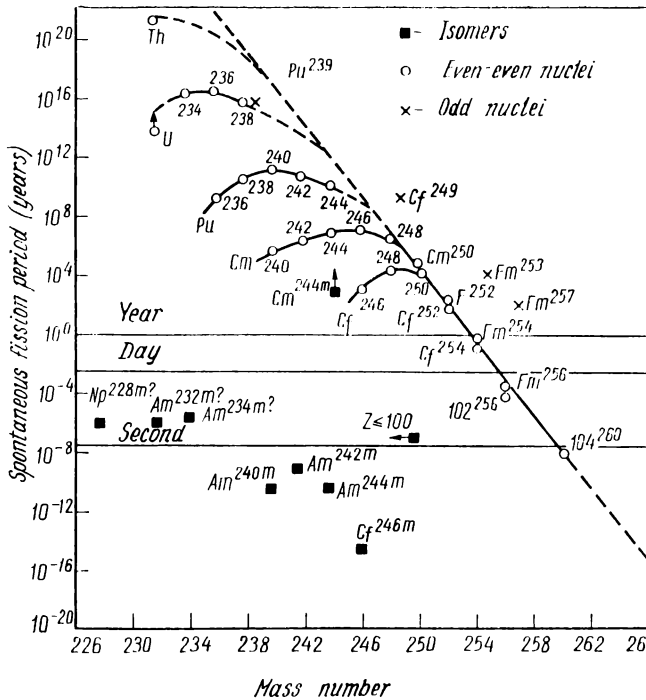
Bohr's hypothesis has been confirmed experimentally by the young Soviet physicists. So, by 1940, the ABC of radioactivity (alpha, beta, gamma) was extended by another component, spontaneous fission.

Uranium can split by itself without any outside effect. But this process is very, very slow. The half-life of uranium-238 is estimated at 10^{16} years and its isotope U^{235} disintegrates ten times as slowly. Obviously it can have no great interest as regards practical utilization of the energy released by fission. In atomic reactors the uranium nucleus splits under the action of neutrons in 10^{-14} second.

Some years later, when a capacity for spontaneous fission was discovered in many heavy elements (thorium-230, thorium-232, uranium-234, neptunium-237, plutonium-239), interest in it grew and many laboratories around the world began a special study of it.

It is now studied by whole groups of scientists and continues to occupy those at Dubna, too.

It turned out: (a) that spontaneous fission was in-



Dependence of the period of spontaneous fission on the mass of nuclei

herent in almost all the nuclei of the heavy elements beginning with thorium, particularly the very heavy, artificially created ones, and (b) that the probability of spontaneous fission rose rapidly with increase of atomic number and began to be a serious rival of omnipotent alpha decay. For superheavy nuclei spontaneous fission becomes the predominant form of radioactive decay.

Whereas the emission of alpha particles is two million times as probable as spontaneous fission in uranium-238, and one million times in plutonium, in californium it is only thirty times as probable, and in fermium (element 100) spontaneous fission is the principal and predominant form of radioactivity.

In studying nuclear fission and calculating its probability, scientists derived what is called the parameter of fission, that is to say the factor determining the capacity of the nucleus to split. This parameter is equal to the square of the nuclear charge divided by its mass number (Z^2/A), that is to say it expresses the ratio of the Coulomb energy of electrostatic repulsion to the restraining surface energy of the nuclear forces. The greater this factor, the higher is the probability that the electrostatic forces pushing protons apart will 'win' over the nuclear forces, and that the nucleus will undergo fission. Obviously, the higher Z is, the greater is this factor, and the more apt nuclei will be to break up spontaneously, mainly the heaviest ones in the Periodic System.

If we look at the drawing on page 132 in which the data on periods of spontaneous fission for the various isotopes available at the time of writing have been plotted, we can see that they vary in a very odd way and differ sharply even for neighbouring elements. For example, the half-life of californium-254 is 60 days, and of californium-250 15 000 years.

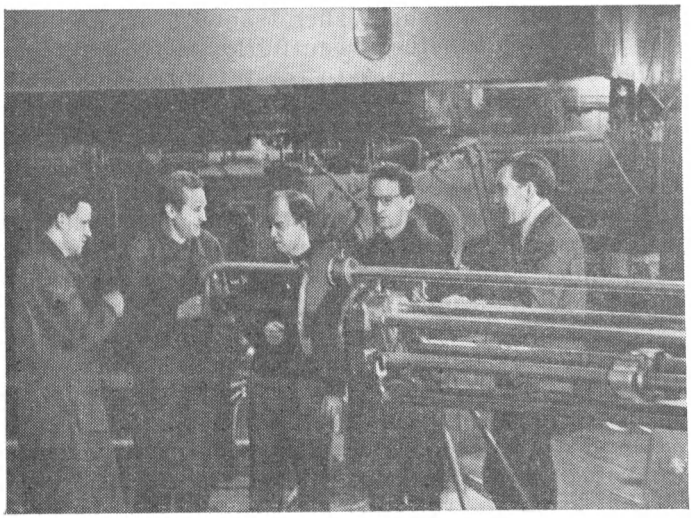
Why? It was incomprehensible. While many of the mysteries of alpha decay had been unravelled, and the half-lives and energies of the alpha particles emitted by isotopes had been calculated quite accurately and could easily be predicted (as we shall see later, most experiments for creating new, unknown elements are based on them), there were still no such forecasts for spontaneous fission.

The model that considered the nucleus as a charged drop of incompressible liquid brought a certain advance in our understanding of the process. And it was from this model that it was deduced that spontaneous fission depended in essence on Z^2/A.

This theoretical proposition was confirmed by the experimental data. Whereas the period of spontaneous fission of uranium is around 10^{16} years, for plutonium it is 10^{10} years, for curium 10^6 years, for californium it is of the order of one year, and for fermium it is a matter of a few hours. More detailed research into the empirical pattern for various isotopes of even elements, however, indicated that the heavier isotopes of an element (with lower Z^2/A) were not as long-lived as lighter ones. Moreover, the odd isotopes of the same elements live some 100 000 times longer than their even-even neighbours. That could not be explained in terms of the liquid drop model.

The Swedish theoretical physicist Sven Johansson suggested explaining it by the 'collective' model of the nucleus. He demonstrated qualitatively that certain nucleons play a major role in the fission process, either accelerating it or retarding it. But his attempts to calculate the absolute life for nuclei as yet unknown did not yield good results. A period of spontaneous fission of 0.02 second predicted theoretically for isotope 102^{256} proved experimentally to be 1500 seconds; for 104^{260} theory predicted $5 \cdot 10^{-6}$ second, but experiment gave 0.3 second. Certain other properties of nuclei had apparently not been taken into account that should have been in order to derive quantitative estimates of the life of distant elements.

It is time now to turn back to the story of what happened in the Laboratory of Nuclear Reactions at Dubna.



S. M. Polikanov's group (left to right): V. L. Mikheev, A. F. Linev, S. M. Polikanov, V. P. Perelygin, A. A. Pleve

It all began back in 1961. Polikanov's group consisted mainly of young graduates of the Leningrad Polytechnical Institute, where Flyorov himself had studied: Victor Druin, a concentrated and purposeful young man, precise to the point of pedantry, and with exquisite manners; Anatole Pleve, a romantic and poet at heart with an exceptionally tenacious grasp and a gift for finding the simplest solution for the most complicated problems; Vsevolod Mikheev, of the clever head and clever hands; Vladimir Perelygin, tall and fair-headed, with an open countenance, famous for his way with glass (about which later); Nicholas Skobelev, the life and soul of the party;

and Vladimir Fomichev. These young men, who supplemented one another beautifully, were making a series of investigations into the transuranic elements and were intent on implementing the slogan on the wall: 'Element 102 Will Be Ours!'

It is difficult to recall now who was then sitting at the control panel, who was assembling the probe, and who was reading the tapes of the recording machine. The target and its layer of uranium-238 were being bombarded with accelerated neon-22 ions. The readings were being carefully watched, and everybody was expecting evidence of the presence of element 102, but the instruments recorded strong pulses of a strange character, the energy and form of which resembled the fission fragments of unknown atomic nuclei.

Could it be the splitting of some as yet undiscovered isotope of element 101 or 102?

That had to be carefully checked. An identical target of uranium-238 was bombarded in exactly the same way with a beam of accelerated oxygen-16 ions. Provided everything was in order, and all the available knowledge of nuclear fission was correct, the reaction should be null as regards transmendelevic elements. Neither element 101, nor 102, could in any way be formed. The charge of uranium is 92, that of oxygen is 8, and $92+8=100$, so that only well-studied isotopes of elements with numbers equal to or below 100, i.e. something like fermium or californium, could be formed. Their alpha decay half-lives are known to be over 30 seconds, and the period of spontaneous fission very much longer.

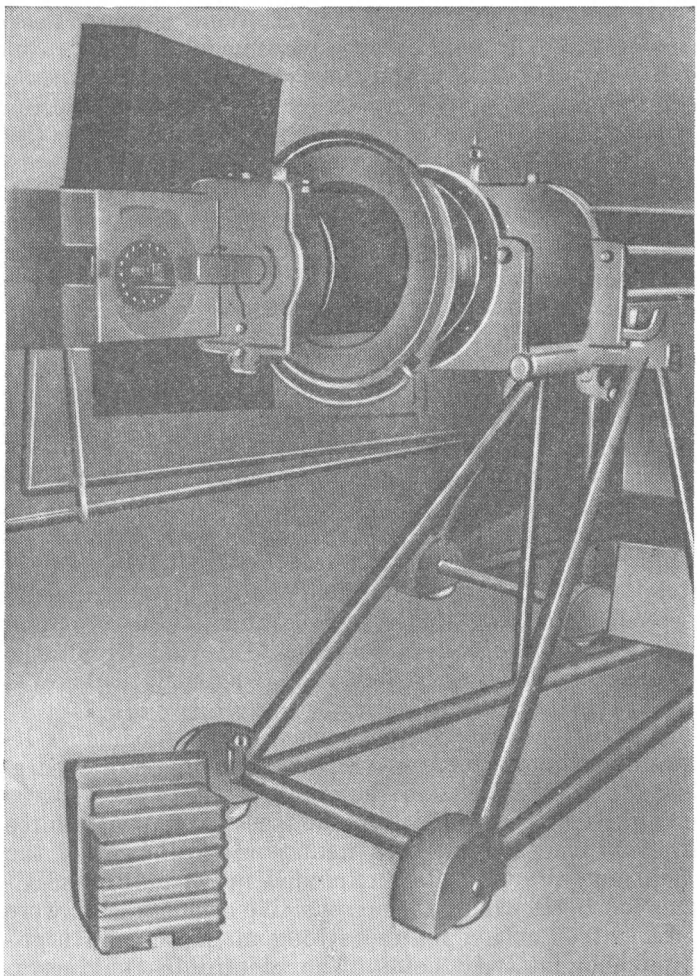
The mysterious pulse 'popped up' in the checking reaction as well, literally mocking the experimenters. Then, after another midnight discussion, Flyorov again came out with his stock: 'Couldn't it be spontaneous fission? Think it over, Sergei.'

It is easy to say: think it over. Well, suppose these really were fragments of spontaneous fission? But what nuclei? The target was made of uranium, and that couldn't have undergone spontaneous fission during that time, whatever the circumstances (its half-life being over 10^{16} years). It was highly improbable that the fission had been induced (by a neon ion), as the life of the parent nucleus of the detected fragments was much longer than 10^{-14} second, the normal life of excited fissile nuclei. Dozens of new experiments were needed to clear up the mystery.

And frankly, it was not easy. In fact it was very, very difficult, much more difficult than the job of a palaeontologist who is trying to re-create a creature that died many centuries ago from a tiny, unidentified fragment of bone.

The first thing was to get all the characteristics of the mysterious fragments correct, i.e. the half-life of the nucleus emitting them, their energy, the reaction cross-section, and a whole lot besides. It called for new techniques. Semiconductor instruments were not then available, so they had to use vacuum tubes. But the equipment had to be set up in the cyclotron chamber where the magnetic field was very intense.

The valves were first arranged along the field's lines of magnetic force but that did not give the necessary amplification of the signal. When they were arranged at right angles to the lines of magnetic force they proved too weak to withstand the power of the field and the thin glass exploded noisily. In conditions of high vacuum the sensitive instruments were put out of action by the strong magnetic and high-frequency electric fields. The electronics engineers, A. F. Linev and B. V. Fefilov, never left the cyclotron for days, trying out all the existing valves that



'The Elephant' (general view)

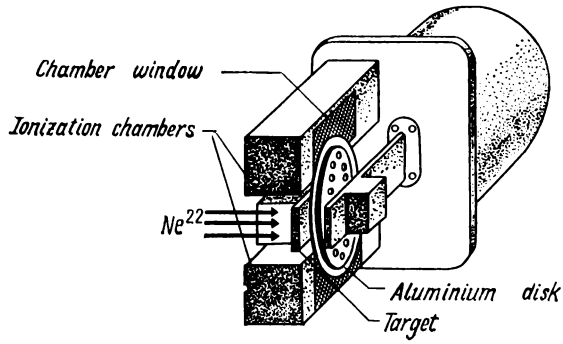
were suitable for mechanical overloads, and succeeded at last in finding absolutely reliable ones.

As there were no semiconductor detectors, ionization chambers were used to detect the reaction products. But ordinary chambers with a single filament (i.e. an axial electric field) yielded confusing signals, as the magnetic field prevented trapping of electrons emerging away from the filament. Remembering his old trick of 'harnessing' the chamber, Flyorov advised stringing seven filaments and getting a 'seven-string guitar', as the engineers called it. Joking apart, the seven filaments gave the chamber a uniform field and caught all the emerging electrons on the dot without fail.

So much apparatus had to be attached to the probe, that it was christened 'the elephant'. Because of the short life of the isotopes of transuranic elements their fission fragments could only be registered, of course, in the immediate vicinity of the cyclotron beam. So the target to be bombarded was mounted directly in the 'elephant'.

The experiment, like most others, was based on the recoil technique developed at the Kurchatov Institute in 1952-3 and widely employed in work on heavy ions. The essence of the method is that target nuclei, having been given quite a high impulse during their interaction with heavy ions, escape and are caught on a rotating collector (a ring of aluminium foil fixed on a disk of stainless steel), which withdraws them from the 'hot zone' and conveys them to the detector (two trap chambers where the reaction products are registered).

The experiment was as follows. A fine coat of uranium was deposited on aluminium foil and this target was put into the cyclotron, by means of the probe, directly in the path of a beam of accelerated ions of



Schematic diagram of the experiment

neon-22. The impact of the ions on the uranium caused interactions; the resulting products followed the same path as the bombarding ions (owing to recoil). The force of the impact was so great that nuclei were knocked out of the target. Ions passed freely through the disk but the recoil nuclei were trapped in it.

When, at last, the physicists had made sure that these really were fission fragments and had measured the tracks of the particles producing such a strong pulse (by means of photographic plates), the half-life of the nucleus proved to be 0.014 second, which was in utter disagreement with all existing ideas of the properties of heavy nuclei.

According to all the evidence, only isotopes of elements with atomic numbers of 100 or less could disintegrate in this way in the experiment. These isotopes had been quite well studied, and it seemed that it should be easy to detect the 'guilty' one among them.

But at this point they had a surprise. From comparisons of the curves and calculations of energies

and cross-sections they found that the periods of spontaneous fission of all the isotopes that could be suspected of such decay were at least 10^{10} times longer than the ones observed. What did that mean? As the half-life of the mysterious isotope was so short that it was impossible to identify it by chemical methods or mass-spectrometry, they had to resort to cross-reference reactions to identify it. The 'masked' isotope was synthesized in various reactions with heavy ions and in reactions from bombarding the targets with alpha particles, deuterons, and even neutrons.

A series of careful experiments that took over two years provided unambiguous evidence that the bombardment of uranium-238 in turn with ions of neon-22, neon-20, and oxygen-16, and ultimately with quite light ions of boron-11 and boron-10, produced a nucleus that split spontaneously into a pair of fragments with a half-life of 0.014 second once in ten million interactions. Its fission could occur in one specific state only and its decay energy was very high.

What was the nucleus that proved capable of such a sharp increase in its rate of spontaneous decay? And what were its mass and charge? They had also to establish whether there were any others capable of the same effect. Or was it a rare bird that was behind the 'mask'?

Polikanov's group made control experiments in Moscow on the cyclotron of the Kurchatov Institute and there, too, bombardment of americium-95 and plutonium-94 with alpha particles, and even deuterons, again and again produced nuclei with fission fragments of similar life (0.014 second).

Analysis of all the data obtained enabled them to 'unmask' the mysterious isotope and show that what had happened was the decay of a nucleus of atomic number 95 and mass number 242 (that is to say there

were grounds for considering that it was americium in an isomeric state). Let me remind you that isomers in nuclear physics, unlike chemistry, are nuclei of one and the same element existing long enough in different quantum states (with different energies and radioactive properties) to be observed.

All nuclei with atomic numbers of 95 or higher had been well studied; their half-lives were known to be many times longer than a hundredth of a second, and their periods of spontaneous fission to exceed ten thousand million (10^{10}) years.

The isotope americium-242, you will recall, had been synthesized long before, and its properties had been well studied. In its normal or, as scientists say, ground state, it disintegrates either by beta decay (emitting an electron) or by electron capture, with a half-life of 16 hours. Spontaneous fission of americium-242 had never been observed, but according to available estimates its period of spontaneous fission should be more than 10^{14} years.

Thus, the probability that spontaneous fission of an americium isomer had been detected in the experiments was 10^{23} times higher than its ground state (10^{23} is a number with 23 noughts and you won't find a name for it in the dictionary).

Such intensification of the tunneling effect could only be explained by some special, excited, or 'metastable' state of the nucleus. It is special because an excited nucleus normally tends to get rid of its excess energy by emitting a gamma-quantum, an electron, or an alpha particle. In the Dubna experiments preliminary alpha- or beta-radiation was excluded, for these modes of decay take hundredths of a second and then fission requires such a high excitation energy in the initial nucleus that it would immediately break up.

The excited nucleus could certainly give off its excess energy by emitting gamma-quanta. But it obviously preferred to disintegrate without electromagnetic radiation. The reason for the preference remained a puzzle.

As soon as the 'culprit' had been identified and it could be said with complete certainty: 'We know you, mask', experiments were begun to establish its specific features, under the code name 'Rare Bird'. It was of paramount importance to find whether any other nuclei could also be put into the state of abnormally fast, spontaneously-fissioning isomers, and to determine the boundaries of the phenomenon discovered.

The experiments mainly concentrated attention on the synthesis of new isomers in reactions with heavy ions.

Others were brought into the work, the physicists Lobanov, Oganesian, Vladislav Kuznetsov, Christian Kekk, and chemists K. A. Gavrilov and Wang Tung-seng. In fact almost the whole laboratory joined it. 'All hands on deck', was the rule there in tough situations, and always proved justified.

Quite new probes were built to replace the 'elephant'; in one of them, built by Druin and Skobelev, the target was mounted at an angle to the path of the ion beam so that all the bombarding ions could react with the largest possible amount of active material. New materials were developed. And now semiconductor detectors, rather than gas chambers, gave precise information on the results of the reaction.

In another probe (the creation of Oganesian, Lobanov, and Kuznetsov), the fission products were transported from the target area by a long, continuous metal belt instead of by a disk. Fast heavy ions flew past it, but recoil nuclei knocked out of the target adhered to it. And whereas the two ionization chambers of the

'elephant' 'picked up' only one period of half-decay (some nuclei disintegrated while moving from the first chamber to the second), the belt made it possible to detect practically all cases and, of course, to measure their lifetimes. By varying the pace of the belt—slowing it down or speeding it up—it was possible to detect the decay of more long-lived or short-lived nuclei respectively. Organic films and glass were used instead of photographic plates, and installed along the whole path of the belt (a scheme developed by Perelygin and his co-workers). The point is that fission fragments leave invisible tracks in glass, which become visible when slightly magnified after etching with weak hydrofluoric acid. Glass, however, is absolutely insensitive to other radioactive products (alpha particles, electrons, protons, etc.). Given the speed of the belt and the length of the glass, it was easy to calculate the life of the nucleus from the number of tracks left in the glass.

They looked, on the one hand, for comparatively long-lived isomers, and on the other hand, for ones with a life so short that they disintegrated in flight, almost before leaving the target.

The main experiments were carried out in Dubna. Another seven isotopes—isomers disintegrating by greatly eased spontaneous fission—were detected and positively identified from the shape of their excitation curves.

So it was probably a matter of the existence of a whole class of hitherto unknown isomers and an entirely new mode of spontaneous fission specific to them; in principle this was a new phenomenon in nuclear physics, the synthesis of ideas about spontaneous fission and isomerism (discovery of which was associated with the name of I. V. Kurchatov).

The interest aroused in world science by this new

phenomenon intermediate between induced and spontaneous fission can hardly be exaggerated. As soon as the first reports were issued spontaneously fissioning isomers became the rage in major research institutes. I confess that I am very pleased and flattered that I was lucky enough to write the first articles on it for popular science journals (all due to that phone call I mentioned earlier).

To get a better idea of the nature of the isomers obtained, and the causes and laws governing their formation in nuclear reactions, it was of interest to measure the energy and spin of isomeric states.

The Joint Institute of Nuclear Research in Dubna is so called because almost all the socialist countries, and scientists from many countries in the West, collaborate in its work. The co-operation is two-way. Scientists come to Dubna, do the work they are interested in, using its unique apparatus, and go home to continue their research. Physicists from Dubna in turn go to other countries to get acquainted with the most interesting work there or to share their expe rience of interesting new research.

So, in order to become familiar with work on spontaneously fissile isomers and to continue his research, Anatole Pleve then went to the Institute of Nuclear Physics in Bucharest, where he studied various aspects of the isomeric ratios for americium with Romanian scientists. Karnaukhov joined Danish scientists in experiments on the electrostatic tandem-generator at the Niels Bohr Institute in Copenhagen. They measured the reaction threshold of plutonium-241, in which bombardment by protons forms a spontaneously fissile isomer, americium-240. Subsequently Druin and Polikanov worked in Denmark at various times.

These experiments, and those at Dubna, revealed

that the excitation energy of the isomers is very high, up to 3 MeV, and their spin small. All the 'normal' isomers hitherto known had considerably lower excitation energies and much larger spins.

At the time of writing about a score of spontaneously fissile isomers of americium, neptunium, plutonium, and californium, with half-lives ranging from a hundred millionth of a second to several minutes, have been produced and were obtained even from such a simple reaction as radiative capture of neutrons.

The abundant experimental data gave rise to various theoretical considerations on the reasons for the formation of this new class of nuclei, and on the possibilities of its existence.

L. K. Pecker suggested that the americium-242 isomer was a specific hexa-quasi-particle state of the nucleus, induced by the breaking apart of neutron and proton pairs, and that its energy would be close to 2.5 MeV.

The hypothesis advanced by Zeldovich, based on a superfluid model of the nucleus, was of great interest. He thought that the nuclear substance, being a superfluid liquid, would be in a state where it formed a drop, that is a nucleus with a quantized axial eddy or vortex. The spin of these eddy isomers, however, would have to be quite large.

Many theoretical physicists were inclined to the opinion that spontaneously fissile isomers were isomers of shape, that is the nuclei were greatly deformed during the reaction. This hypothesis was considered, in its general form, by Flyorov. It was also advanced by Malov, Polikanov, and Soloviev who demonstrated the possibility of two-quasi-particle isomeric states.

The hypothesis that received the widest recognition

at the international conference on nuclear structure in Dubna in July 1968 was the one advanced by V. M. Strutinsky of Moscow. His calculations indicated that the central fission barrier, regarded for a quarter of a century as a smooth hump that the nucleus had to be heaved over before it broke up, had a complex structure and in all probability was not one hump but two like the back of a Bactrian camel, with a second potential well between the humps.

The excited nucleus could remain in the second potential well, between the humps, after deformation, forming a 'shape' isomer. As the second hump is much lower and thinner than the total barrier, the probability of a nucleus undergoing spontaneous fission from this state is greatly increased. Exclusion of gamma emission (which had so far not been observed in spontaneously fissile isomers) could also be accounted for by the essential difference between the deformation of an isomer and that of a nucleus in the ground state.

From Strutinsky's standpoint, it would be possible to explain the resonances, then quite incomprehensible, occurring during plutonium and neptunium fission induced by neutrons of mean energy, discovered by French and Belgian scientists. These resonances could now be interpreted as a manifestation of the level of a nucleus in the potential well between the humps.

Thus, the effect discovered at Dubna stimulated development of the fission theory underlying the whole of nuclear power engineering.

There is another hypothesis, linked with the view of the nucleus as a system of joint interactions, based on the model of a gaseous ball. D. F. Zaresky and M. G. Urin have developed ideas on the effect of the mass coefficient on tunneling effect (the probability

of penetration through the fission barrier). They believe that there can be isomeric states in which pair correlations between nucleons have completely disappeared and the value of mass coefficient corresponds to the hydrodynamic limit. The probability of spontaneous fission should then be 10^{16} times higher.

It is difficult to say which hypothesis is more valid. Obviously, as with the model of nuclear structure, they all contain a certain grain of truth. None of them denies that the strong exclusion of radiation transitions from a nuclear state with an energy around 3 MeV, and the very small spin, is due to the marked difference between the shape of the nucleus in its ground and isomeric states, and that it is this marked deformation that alters the correlation of forces within the nucleus so that it becomes most advantageous to break into two.

What will actually happen, perhaps, will be a reconciliation of all the hypotheses advanced when there is more precise knowledge of the structure of the nucleus and the nature of nuclear forces. In any case, explanation of spontaneously fissile isomers will be a significant step toward developing an exhaustive theory of the atomic nucleus.

HOW ARE NEW ELEMENTS CREATED?

Let us continue our journey, and go on now to the top of our map (p. 92) (i.e. to the lower right-hand corner of Mendeleev's Table), where the heaviest transuranic elements are.

Transuranic elements may once have existed on our planet when it was being formed, but thousands of millions of years ago they underwent radioactive decay and can now only be produced artificially. Therefore, the upper part of our map is man's undisputed

realm, the right to rule which he has won by his powerful intellect, dedication, and persistence in achieving his goal.

Since the day the first transuranic element was discovered, or rather created, thirty years have passed; in that time thirteen new elements have been incorporated into Mendeleev's Table. They are not simply thirteen new chemical symbols. And least of all is this synthetically created family like thirteen handsome, but useless, trophies crowning heroism and effort.

From what we have said so far it should be clear that the very discovery of the heaviest elements in the Universe has extended man's knowledge of nature, of the structure of the atom and nucleus, of the basic principles of the structure of matter, and of the fundamental laws governing the world around us.

But any really profound and fundamental research often leads to such unexpected and important practical consequences that it becomes a turning point in the history of technological progress. So it was with the transuranic elements. We already know what plutonium brought mankind. With the building of fast reactors, i.e. reactors in which fast neutrons rather than slow ones are used to induce uranium fission, the plutonium-239 isotope is becoming increasingly important as a nuclear fuel. It is produced in fast reactors from naturally occurring uranium-238, which is not fissile in normal conditions.

In ordinary reactors, in which slow neutrons induce uranium fission, uranium-235 is used as fuel, but there are only seven kilograms of it in a ton of natural uranium-238. The rest of the U-238 is 'waste' and the technique of separating it is very complicated. It is this 'waste' that is brought into the fuel cycle by me-

ans of plutonium and turned into useful fuel, thus immeasurably increasing reserves of nuclear fuel.

No less benefit can be derived from plutonium-238. This isotope has a half-life of 90 years and can be a compact and quite powerful source of electricity through conversion of the heat of its radioactive decay in thermo-electric or thermo-ionic devices.

Very light, compact power installations have already been built in the USA and the USSR, using plutonium-238. Because of their lightness they are indispensable as power sources for spacecraft. And as they emit very little radiation they are comparatively safe to handle.

The first plutonium-238 nuclear battery was put into orbit on 29 July 1961 and is still sending signals back to earth. A similar source may be taken to the moon by astronauts to supply power for radio transmitters for a certain time.

Such a power source could be used for pacemakers for heart patients, and Pu-238 is being tried out with an artificial heart.

It is estimated that demand for Pu-238 for nuclear batteries in space will run to tons in the next decade or two, and if the idea of an artificial heart materializes, demand will be substantially greater. Luckily, Pu-238 is not difficult to obtain as it can be produced in reactors by bombarding neptunium-237 with neutrons.

Interesting observations on the practical utilization of other transuranic elements were made by Glenn Seaborg on 8 November 1966, when they were dedicating the Transuranium Research Facilities at the Oak Ridge National Laboratory.

It was possible, he said, to produce curium-244, for example, an isotope with a half-life of 20 years, by intense neutron bombardment of plutonium, and

it, like plutonium-238, could be used as fuel for nuclear batteries. He was specially interested in its large-scale production because of the tremendous amounts of transuranic by-products that would inevitably result. And if it proved to have the properties required for widespread use as a power source, production by the ton was feasible by converting plutonium breeder reactors over to its manufacture.

When he recalled that their first experiments with curium-244 in 1961 had involved picogram quantities, (that is quantities of the order of a million-millionths of a gram), tons seemed almost unimaginable, Seaborg said, for they were talking of an escalation of production of the order of 10^{18} (a billion billion times).

Isotope power sources created very high temperatures during the conversion of heat into electricity. Three grams of a mixture of oxides of curium-242 and americium-241, for example, gave a temperature of 1000°C, which provided an inkling of their potential. Other isotopes, curium-244 for instance, also gave high temperatures. The power output was around 120 watts per gram of curium-242, around three watts per gram of curium-244, around half a watt per gram of plutonium-238, and it was available for several years, diminishing only as the isotope decayed.

Californium-252, which is obtained by successive capture of neutrons in high flux reactors, could be used as a point source of neutrons in radiography, or as a portable and reliable source for neutron activation analysis (a method of detecting trace amounts of chemicals by activating them by neutron bombardment) in places where it is not possible to use conventional neutron generators. Californium-252 could also be used in medicine for treatment, diagnosis, and other purposes.

However impressive the possibilities of using heavy

transuranic elements seemed at that time, Seaborg continued, he believed that even more significant fields of application would be found in the future. And if it was acknowledged that the deepening of our knowledge of nature alone justified fundamental research into heavy elements, their potential applications were an even greater justification. He predicted that study of transuranic elements would continue to interest science for many years to come.

There is no need to wonder, then, at the titanic efforts that have been made and are being made to advance further beyond uranium.

The discovery of element 101 (mendelevium), which begins the second hundred on the list of elements known to man, has become a milestone in the synthesis of transuranic elements. As we have already learned, the physical methods previously employed to produce elements and the chemical means used to identify them had been exhausted with its synthesis. To make the next step, quite new equipment and instruments were needed.

Element 101 was the first transuranic element to be discovered literally by counting atoms. The exceptionally small yield of heavy elements is mainly because of the tiny amounts of starting material used as targets (when the heaviest element available is used). Another reason is the small reaction cross-section, i.e. the low probability that a fast projectile particle will hit so minute an area as the target nucleus. But the main difficulty is that even if the projectile hits the target, it is more likely to split the latter immediately into two than to be absorbed by the nucleus with subsequent formation of a new element.

A compound nucleus is more apt to break up, due to the tremendous excitation induced in it by the projectile, than to eject neutrons and be transmuted

into the nucleus of a new element. You may remember that the probability of two nuclei fusing is proportional to their size. The cross-section of a compound nucleus formed through fusion is 10^{-24} square centimetre, a figure that is taken as the unit of area for measuring nuclear cross-sections, and is known as a barn. The formation cross-section of a new isotope, i.e. the probability of nuclei 'surviving', having got rid of the excess energy by ejecting neutrons, is many orders of magnitude lower. When we say that the cross-section of a certain reaction is 10^{-30} square centimetre we mean that only one compound nucleus in a million survives having ejected neutrons.

Hence it will be clear how complicated it is to calculate the mass of the interacting nuclei without neglecting any of the factors involved, i.e. to select the isotopes for the target and projectiles and their energies, and how difficult it is to obtain a very big yield of new nuclei.

After the problem of producing an ion flux of sufficient energy and uniformity had been solved, there was the problem of the target. There can be no doubt that it too was Problem No. 1. The problem here, however, was not the complex and bulky facilities needed to accelerate multiply charged ions but rather the completely new demands made on applied physics and chemistry, whose arsenal had been considerably exhausted.

The literature had no data, save insignificant indirect indications, on the interaction of a heavy ion with a substance. Yet the interaction of multiply charged ions and the material of a target or collector plays an essential role in the delicate operations of establishing the 'identity' of the isotope produced.

What is the target for nuclear experiments like? It is a minute piece of very thin metallic foil, finer

than a human hair. An even finer coating of the active material needed for the reaction of the element is deposited electrolytically, or by some other means, on the foil. A target like that is used when the recoil nuclei from the reaction are trapped by a collector, that is when nuclei are knocked out of the target. When the reaction products remain in the target, it can be a little thicker; it is then dissolved for radiochemical analysis (as was done with berkelium and einsteinium).

Imagine that the target is being bombarded with accelerated ions. They will hit it and the collector and, in addition to nuclear interactions, will cause various changes in their materials connected with ionization and the changes in their crystal lattices. Atoms knocked out of the lattices will be in a micromolten state and continuous chaotic motion. If there are any impurities in the target itself, they may, due to the high chemical activity of ionized atoms, interact chemically with the material both of the apparatus and of the target to form various, sometimes very complex, chemical compounds. And being very active they will have an essential effect on the accuracy and reliability of the data on the chemical behaviour of an isotope.

When it came to identifying element 102, when reliable and precise chemical methods had to be abandoned, the 'identity' of the new element could only be established by physical techniques, i.e. from its radioactive decay products, e.g. by the character of the tracks of alpha particles. The time for identification was thus reduced from ten minutes or so to a few seconds. And, having only the tracks of alpha particles to go on, they had to be very, very apprehensive lest side processes in the target and collector gave rise to alpha particles of the same energy but

having not the slightest connection with transuranic elements. They might arise, for example, from thorium ($Z = 90$) produced by nitrogen bombardment ($Z = 7$) of a target containing even the tiniest amount of bismuth ($Z=83$).

From that angle a whole group of elements (lead, bismuth, and thallium) is, in general, extremely dangerous; for when bombarded they emit high-energy alpha particles (up to 12 MeV). The probability of these background alpha-particles arising is very high; the formation cross-section of element 102 from the interaction of oxygen and plutonium is of the order of 10^{-32} square centimetre, and the formation cross-section of alpha activity in the case of an oxygen-lead interaction 10^{-26}. To be really certain, therefore, that the observed effect was attributable to element 102, and only to it, they had to be, not 100 per cent sure, but 100 000 per cent certain that there was less than one hundred thousandth of one per cent of lead, bismuth, thallium, or any other element as an admixture in the target material.

With techniques sensitive enough to detect new elements with a cross-section of 10^{-34} square centimetre, concentrations of elements of one ten millionth of one per cent are dangerous!

A layer of graphite can form on the target under the action of a dense ion beam, a possible reason being the burning of oil vapour from the cyclotron. Under bombardment the precipitated oil disintegrates but the graphite remains, and then not an atom can be pulled off the target.

How was this annoying phenomenon to be avoided? First of all, it was necessary to raise standards of target purity to eight, or even nine, nines after the decimal point. Conventional methods were of no use for such purity. The only way out was to produce a

substance of uniform isotope composition by complex modern techniques for the separation of isotopes. The purity of the neon-20, and neon-22, and oxygen isotopes supplied to Dubna is now almost absolute (99.99999999 per cent).

Before an experiment the target backing can first be heated in a vacuum so that impurities are volatilized. That is what Ghiorso's physicists did at Berkeley when preparing to synthesize element 103. They used a target of californium deposited on thin nickel foil. The foil was first heated to 1000°C in a vacuum. Then californium obtained by electrolysis was electrodeposited on it, and the whole thing heated once more to 1000°C for some minutes by electron bombardment. In this intricate way the californium was converted into a very stable and dense coating on the nickel foil and admixtures of lead and bismuth were completely evaporated.

In addition to these methods, there is another, purely experimental, way out, and that is to check the results obtained many times. And 'background experiments' can be performed, in the same conditions, using a substance known not to produce the element wanted. Remember the experiment in bombarding uranium with oxygen, when spontaneously fissile isomers were discovered?

When one is trying to produce a new element, it is necessary so to vary the conditions of the experiment that no doubts remain about the stability of the effect. It is important, as well, to select the target and projectile materials not only from the aspect of optimum calculation of the nuclear interaction but also taking into account the possible effect of impurities and the target material. For example, when element 102 was being produced three combinations could have been employed: (a) plutonium plus oxy-

gen, (b) californium plus beryllium, or (c) uranium plus neon, i.e. either a light target and a heavy ion or a heavy target and a light ion. From the standpoint of physics it was rather better to take a heavier target, though the yield would then be small; but from the angle of radiochemical effects and convenience light targets were preferable, being less radioactive.

The importance of these rather dull arguments and explanations will become clear when we learn about the adventures, or rather misadventures, of element 102. Though it had no name but only a number, it managed to have a chequered career packed with dramatic events.

July 1957 was unusually hot both in Europe and in America. Everyone who failed to 'get back to nature' from torrid humid New York tried to relax as late as possible in the evening when there was an illusion that it was cooler. That was why it was quite lively at the building of the *New York Times*, despite the late hour, when the news flashed: 'Element 102 discovered. Named nobelium.'

Day was already dawning in London and Stockholm. The newspapers there were already announcing the same thing: 'Element 102 discovered.'

It was a fine morning in Moscow, too. Vyacheslav Shchegolev, a thin, fair-haired young man quite unknown in either Europe or America, was in a local train going from Moscow to Dubna, where he had been invited to work in Flyorov's laboratory. He was mulling over various thoughts and worries; he was starting out on life; everything lay before him; in his pocket was a scarcely dry diploma from the Leningrad Polytechnical Institute confirming that he had qualified in a very romantic and fascinating profession, physics. He was going to an institute where the best brains of several countries had been brought

together, and he was moving to a brand new town where he would live for years, and to a different world from his native Leningrad. There was no room left for element 102 in these streams of thoughts. And no one in the world would have thought then of linking these events.

That memorable summer of 1957 an international team of scientists from the Argonne National Laboratory in Chicago, the Atomic Energy Research Establishment in Harwell and the Nobel Institute for Physics in Stockholm were trying to synthesize element 102, targets of a mixture of curium isotopes were being bombarded in a cyclotron with a small beam of carbon-13 ions of quite varied 'colour'.

They were using the 'recoil technique' to separate any possible nuclei of element 102 from the thin curium targets. The products formed in the nuclear reactions resulting from bombardment were knocked out of the target by the bombarding ions and picked up on catchers and then treated chemically and analysed in ionization chambers with a view to detecting alpha activity from the disintegration of element 102.

In extremely difficult experimental conditions involving many runs, the Stockholm group succeeded in detecting some 20 alpha particles of 8.5 MeV and a half-life around ten minutes in the ionization chamber. Activity in the ion exchange column was as had been expected; two or three drops were eluted from the column immediately after passage of a full volume of eluant, i.e. more quickly than the lighter actinides. This suggested that the 20 atoms recorded could only be element 102, and probably, its odd isotope 253 or 251. It must be odd because the astonishing, quite incredible 'longevity' of the alpha activity obtained was otherwise inexplicable. And only isotopes of odd

mass number gave such a delay in alpha decay. They had estimated that the normal 'permitted' decay for an isotope of element 102 with alpha particles of a similar energy (8.5 MeV) would be only ten seconds.

The international team reported positive identification of element 102 and suggested calling it 'nobelium' in honour of Alfred Nobel, whose name was borne by the Stockholm Institute where the work was done, and the influence of which on the advancement of world science could hardly be exaggerated.

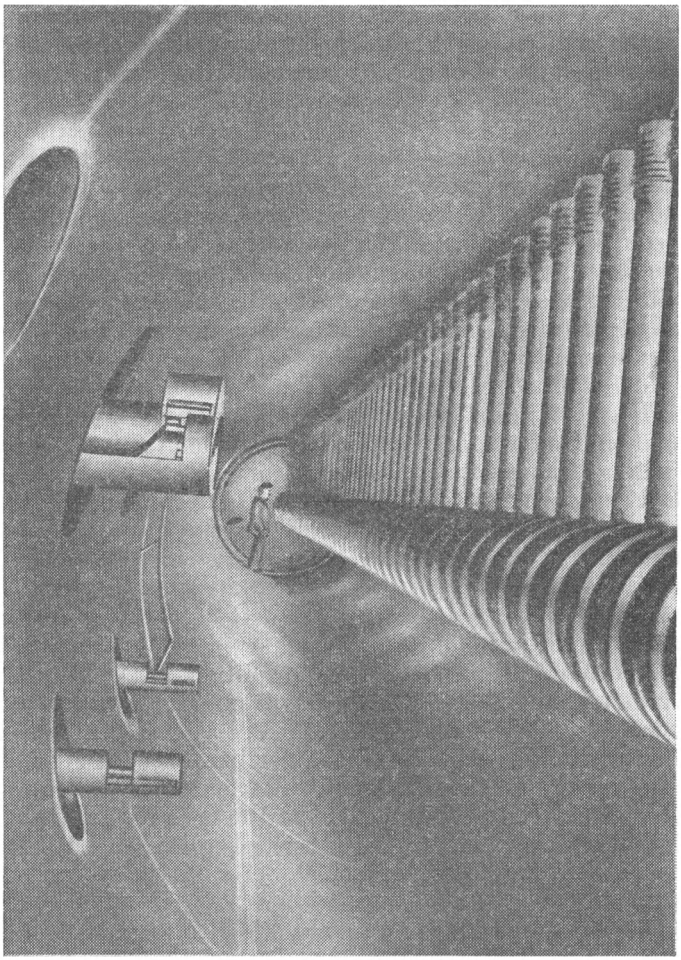
The name was accepted almost immediately by the Commission on Atomic Weights of the International Union of Pure and Applied Chemistry.

The Stockholm team did not repeat their experiment, but efforts were made to reproduce it at the Radiation Laboratory in Berkeley and at the Institute of Atomic Energy in Moscow. All their attempts to get ten minute alpha activity with the same techniques and in the same conditions, however, proved in vain.

In Berkeley the powerful HILAC accelerator (also called the 'atom-making machine') was replacing that honourable 'veteran', California University's 60-inch cyclotron, for accelerating heavy nuclei (ions), and had only just begun operation.

Whereas the strength of the cyclotron beam at the Nobel Institute was between 0.03 and 0.1 microampere, HILAC's was 0.2 μA; and whereas the beam of the Swedish machine was 'spread' over a range of energies from 70 to 100 MeV, HILAC produced a monochromatic (homogeneous) one.

The American physicists bombarded curium targets with the carbon-13 and carbon-12 ions in a range of 60 to 100 MeV and began the analysis within eight minutes of each bombardment. In the other experiments



The HILAC (Heavy Ion Linear Accelerator)

the energy range had been 5 to 9 MeV per nucleon and analyses made every 30 seconds.

In these conditions at least 100 atoms of the new element should have been produced, but in not a single case over several months did they obtain energies of 8.5 MeV for alpha-particle activity and a half-life of ten minutes. That was because there was still treacherous guile in targets not sufficiently refined of slight admixtures of lead, mercury, and other elements!

In the work carried out in Moscow in 1957-8 on the 150-centimetre cyclotron at the Institute of Atomic Energy a new technique for physical identification of the element was employed for the first time, which consisted essentially in rapid mechanical transfer of the nuclei or reaction products escaping from the target to radiation detectors recording alpha particles or fission fragments. (A quite advanced technique we became acquainted with in Dubna where it was used in experiments to detect proton radioactivity and spontaneously fissile isomers. Remember the rotating disks and endless metal conveyor belt for withdrawing recoil nuclei?)

In the early Moscow experiments nuclei were knocked out onto an aluminium catcher that was shuttled back and forth every 1.5 to 2.0 seconds across the two meters from the bombardment zone to the nuclear photographic emulsions that served as alpha-particle detectors. Target of plutonium-241 and plutonium-239 were bombarded with accelerated oxygen-16 ions. The first target was subjected to 40 bombardments of three hours' each. Exposure time in the beam and at the photographic plate was eight seconds; the catcher cycle took three seconds. As a result 90 alpha particles were detected with energies between 8.2 and 9.0 MeV.

The second target, of refined plutonium, contained

a much smaller admixture of lead. Ten three-hour bombardments in similar conditions resulted in the detection of 20 alpha particles with energies between 8.2 and 9.0 MeV.

Every measurements with photographic emulsion, however, are not sufficiently accurate, so the results were then processed to make them more precise. When corrections were applied, the high-energy alpha particles detected (which could be attributed to decay of element-102), gave a half-life for this isotope of not less than two seconds and not more than forty. The Moscow workers did not succeed in making a detailed study of the reaction leading to the formation of the new emitter, but it could be supposed that it was produced in two types of decay involving the emission of either four or five neutrons.

Anticipating things a little, let us remark that the very much more exact experiments performed later revealed that these properties closely resembled those of isotope 102^{252}, which has half-life of 4.5 seconds and alpha-particle energy of 8.41 MeV. It was this isotope, apparently, that Flyorov's group had succeeded in detecting in the following nuclear reaction:

$$\text{plutonium}^{241}_{94} + \text{oxygen}^{16}_{8} \rightarrow 5 \text{ neutrons} \rightarrow 102^{252}$$

The main contribution of the Moscow team (which they owed to the endless checks and disproofs introduced by Kurchatov) was their exposure of the 'treachery' of targets. That was how they detected an enormous rise in alpha-active background, due to the effect of ion bombardment on the admixtures of lead and lighter elements in the materials of the target and catcher. The cross-section of this background alpha-radiation was a million times higher than the formation cross-section of element 102. Thus groups of alpha particles

with energies of 11.65 and 8.87 MeV were detected for the first time in Moscow. It proved later that they were caused by the decay of polonium isomers resulting from the interactions of oxygen and lead in various transfer reactions.

The Moscow team spared no efforts, paid special attention to the 'background problem' and succeeded in developing a highly sensitive activation method of analysing the targets and catchers for lead content and an efficient technique for refining the target material of the impurities always in it; and all that later stood in good stead for many experiments at Dubna.

The elucidation of all these circumstances enabled Seaborg, Ghiorso, and others to suggest that the alpha activity observed in Stockholm might have been caused by the decay of lighter elements like lead, bismuth, etc., that had not been refined from the material used and mistakenly attributed to element 102.

Less than a year had passed since the announcement of the discovery of nobelium, and all that remained of its name, as journalists bitingly commented, was the 'No'.

In April 1958 a team at the Radiation Laboratory in Berkeley, consisting of Seaborg, Ghiorso, Thorbjorn Sikkeland, and J. R. Walton, mounted a new experiment to synthesize No. 102. To improve the accuracy of identification they employed an original, 'double recoil' technique specially developed by Ghiorso for the purpose.

The experiment was planned and carried out as follows. Fine nickel foil was carefully coated with a mixture of curium isotopes (95 per cent curium-244 and 4.5 per cent curium-246), which used up the whole stock they had built up over several years by bombarding plutonium with neutrons.

The target was put into a container filled with helium and placed in the accelerator's beam. The projectiles were carbon-12 ions accelerated to high energy. To produce a nucleus with 102 protons, six protons from the carbon nucleus had to combine in the reaction with the 96 protons of the curium nucleus:

$$\text{curium}\,^{246}_{96} + \text{carbon}\,^{12}_{6} \rightarrow \text{element}\ 102\,^{254} + 4\ \text{neutrons}$$

Half the 102^{254} nuclei decayed in about three seconds to fermium-250 nuclei with one alpha particle to each decay event.

The radioactive properties of fermium-250 are well-known: its half-life is 30 minutes with the emission of alpha particles with an energy of 7.43 MeV. Thus, it can be identified chemically in an ion-exchange column by a technique which is also well known.

So element 102 should be identifiable from its daughter products, which could be isolated by physical and chemical means.

When HILAC's beam of carbon nuclei hit the thin target, the atoms of element 102 born were ejected into an atmosphere of helium. At that point they did not possess a complete set of electrons and were essentially positive ions, and for that reason were beautifully attracted by the negatively charged metal conveyor belt positioned directly beneath the target.

The belt, travelling at a certain speed, then passed under a trap or 'catcher' made of metal foil, which in turn was charged negatively in respect to the belt. Half the daughter atoms of fermium, produced as a result of alpha decay of element 102, escaped from the surface of the belt and were drawn to the catcher.

The period of bombardment corresponded to the half-life of the 'daughters', i.e. the fermium atoms destined for investigation. After bombardment, the

foil of the catcher, with the daughter nuclei adhering to it, was cut into five equal sections, transversely to the direction of the belt's movement. The sections were then analysed simultaneously in radiation counters. The position of the stationary catcher for fermium-250 atoms proved to correspond to the three-second half-life of the parent isotope, i.e. to the isotope of element 102.

To isolate the daughter decay product, fermium-250, chemically the radioactive materials of the catcher were dissolved and put into an ion-exchange column. A tiny droplet of liquid containing fermium-250 yielded nine decay events, which meant that it contained nine atoms of fermium.

In the next, more direct experiments, the charged ions of element-102 ejected from the curium target were trapped on a negatively charged belt coated on both sides with aluminium, which was drawn rapidly into the alpha-particle counter of an ionization chamber with a grid for direct measurement of the element's half-life and the energy of its alpha particles. While one section of the belt was being analysed, another was being bombarded, and so on.

The half-life was found to be three seconds and the energy of the alpha particles 8.3 MeV. To their great surprise they also noticed fission fragments with the same half-life of three seconds, the result of spontaneously disintegrating atoms and constituting around 30 per cent of the number of alpha decay particles.

The American scientists interpreted the results of the first and second experiments as the discovery of the isotope of 102^{254}.

Unfortunately, their interesting work was abruptly halted by an accident, the curium explosion we have already mentioned. The helium-cooled window between the curium target, and the HILAC tube blew

up because of a chance increase in pressure, and the helium destroyed the curium target. The accident not only wiped out their whole stock of precious curium but was also a psychological shock. Those involved admitted that they became extremely gun-shy when using highly alpha-active targets. It was only some years later that they decided to repeat the experiments, after taking the most elaborate precautions.

Since the Swedish results had proved erroneous, the Berkeley team thought it their right to suggest a new name for element 102 and, officially or otherwise, expressed a wish to christen it rutherfordium in honour of Ernest Rutherford, the pioneer of nuclear physics.

Having abandoned all manipulations with highly active targets because of curium contamination, the Berkeley physicists concentrated on 'quieter' plutonium ones. But HILAC was not suitable for producing ions of elements heavier than oxygen.

To obtain element 102, such a combination of small cross-sections and weak beams was almost ineffectual. So Ghiorso's group decided to go for No. 103 instead by bombarding small amounts of californium with boron ions.

In the spring of 1961, after nearly three years' persistent work Ghiorso, Sikkeland, A. E. Larsh, and R. M. Latimer detected an isotope of element 103 with a half-life around eight seconds in the following reactions:

$$\text{californium } {}^{252}_{98} + \text{boron } {}^{10}_{5} \rightarrow 103^{257} + 5 \text{ neutrons};$$

$$\text{californium } {}^{252}_{98} + \text{boron } {}^{11}_{5} \rightarrow 103^{257} + 6 \text{ neutrons}$$

The scheme and technique of the experiment were almost the same as those employed in the second, direct experiments to synthesize element 102^{254}.

Boron ions bombarded the californium target, generating positive ions of element 103, which were caught on a moving, negatively charged, copper belt. Alpha-particle counters (silicon-gold detectors) measured the decay rate of the isotope and the energy of the alpha particles emitted by it in decaying to mendelevium:

$$103^{257} \xrightarrow{\text{half-life 8 sec}} \text{mendelevium } {}^{253}_{101} + \text{helium } {}^{4}_{2}$$

In this way it proved possible to identify an isotope of element-103 emitting alpha particles with an energy of 8.6 MeV, and a half-life of eight seconds. Many control experiments using various targets and bombarding particles were performed so as to demonstrate that the activity was irrefutably not due to lead, bismuth, or polonium, since the properties of their radioactive isotopes were close to those of the isotope of element 103. As with No. 102, it was impossible to identify No. 103 chemically. Its discovery was based solely on physical evidence.

The scientists who created the new element proposed calling it lawrencium in honour and recognition of Ernest O. Lawrence, inventor of the cyclotron and founder and director of the Radiation Laboratory at Berkeley.

* * *

The Learned Council of the Joint Institute of Nuclear Research in Dubna meets twice a year, usually at the beginning of January and end of May. The most eminent scientists of Bulgaria, Czechoslovakia, the German Democratic Republic, Hungary, Poland, Romania, the Soviet Union, and other member countries attend. Around the horseshoe table in the conference hall can be seen venerable members of academics and

professors, the flower of science, listening attentively to young scientists and heads of laboratories reporting on the most interesting work done in the past half-year. Then they discuss plans and schemes for the next half-year. Before each one on the table is the flag of his country. The solemnity of the occasion is slightly marred by the school blackboard in the middle of the hall and, in May, by the common wild flowers in vases on the table.

During the evening session on Friday, 31 May 1963, the attention of all members of the Learned Council concentrated on Eugene Donets, a tall, handsome young man in a light open-necked shirt, who led a team consisting of himself, Shchegolev, and Victor Ermakov. Donets was reporting discovery of a very heavy isotope of element 102, with a mass number of 256.

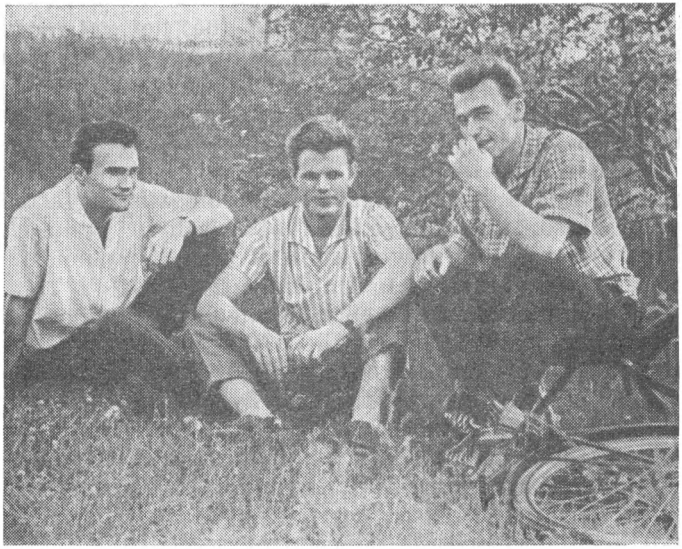
'Let me tell you how the heavy isotope 102^{256} was synthesized. It is clear now that it can be obtained by the following reaction:

$$\text{uranium}^{238}_{92} + \text{neon}\,{}^{22}_{10} \rightarrow 102^{260} \rightarrow 102^{256} + 4n.$$

The compound nucleus can eject four neutrons and will be transmuted into an isotope 102^{256}. This nucleus will be in a non-excited state in the ordinary sense, and its radioactive properties can be studied in that state.

'We can now say that it did not take very great ingenuity to produce this nucleus. It was much more difficult to investigate its radioactive properties and to find how many nuclei were produced in any one experiment.

'In reactions with heavy ions the number of products obtained resembling the nuclei of new elements in radioactive properties is much greater (hundreds and thousands of times more) than the number of nuclei



Eugene Donets' Dubna group: (left to right) Donets, Victor Ermakov, and Vyacheslav Shchegolev

of the elements being sought. And these products may contain nuclei whose radioactive properties are very close to those expected for elements 110 or 115, to say nothing of 102.

'In spite of all these difficulties, it is at least possible to sythesize nuclei of a new element, study their properties, and clarify how they are produced in a particular nuclear reaction.

'The alpha decay is the transformation of a nucleus of element 102^{256} into two nuclei—one of helium with a charge of two and mass of four and one of element 100, fermium, with a charge of 100 and a mass of 252. If we detect alpha particles with an energy correspond-

ing to that of isotope 102^{256}, that does not yet mean that we have synthesized that isotope. But if with alpha decay, element 100 is also obtained with a mass number of 252, that means that alpha decay of isotope 102^{256} has occurred.

'It is that principle for recording an alpha-active nucleus by its daughter product, which was suggested by Ghiorso, that underlies the technique we used. It is based on the law of conservation of momentum and is quite feasible to implement.

'If alpha particles are ejected when quiescent nuclei of element 102^{256} decay, the 100^{252} nucleus receives a recoil energy of approximately 100 keV, which is sufficient for it to pass through five to seven atomic layers of any substance. It is a very high energy and we can make use of it.

'From what I have said, the operating principle of the apparatus we used to synthesize isotope 102^{256} can be understood. It consists of a gas-filled probe located in a vacuum chamber in the beam of a big cyclotron. A beam of accelerated neon-22 ions strikes the probe through a special vacuum-tight window.

'As the beam is quite powerful, lighter targets could be used. We bombarded a uranium target. On striking a uranium nucleus, an ion usually splits it into two nuclei of equal mass. But there are exceptions. Once in a 100 million cases the compound nuclei does not split, but successively emits four neutrons to become a nucleus of element 102.

'Behind the uranium target there is a closed space with a moving wall (formed by the conveyor belt). The other walls are stationary. Under the impetus of the bombarding neon nuclei, the nuclei of element 102^{256} are knocked out of the thin layer of uranium into the gas, where they are slowed down through collision with its molecules and dispersed to the walls

of the probe. They are then withdrawn from the bombardment zone by the belt. If alpha decay of element 102 has occurred, nuclei of element 100 will be attracted to a special catcher by the electric field.

'Since the half-life of element 100 is known, this experiment can be carried on for a long time until enough of its nuclei have been accumulated to permit determination of the half-life of element 102 from their distribution and the pace of the belt.

'These experiments have been carried out with success. It has been established that the isotope 102^{256} is alpha active and has a half-life of several seconds.

'The number of nuclei of element 102 produced during a definite period of bombardment depends on the energy of the bombarding neon ions.

'It is easy to understand why. When the energy of the neon ions imparts excitation to the compound nucleus, the latter is not excited enough to emit four neutrons if the energy is low; on the other hand, if it is very high, four neutrons cannot cool it down, a nucleus of element 102 can only be produced in the non-excited state within a very narrow band of energies.

'The experiments were continued. We studied the instability of 102^{256} isotopes in regard to spontaneous fission into two fragments. This nucleus proved to be quite stable as regards spontaneous fission. Its half-life is around 1500 seconds.

'All the experiments were performed most scrupulously and all results that might contradict the final positive conclusion were repeatedly verified by various cross-checks.

'It was not only that we were dealing with a new nucleus but that its properties, as predicted by theory differed greatly (to be exact 100 000 times) from those we obtained experimentally.

'The period of spontaneous fission predicted theoretically by Sven Johansson was around 0.01 second, but the experimental period determined by us was over 1000 seconds.

'I think that is a sufficient illustration of how careful one must be in predicting nuclear properties.'

Donets did not say in his report that the more than 700 decay events of the new isotope registered by them were many times more than the results of any of the experiments performed earlier. Nor did he say that Flyorov had insisted on them attempting to refute their own results and performing hundreds of experiments, and that, with no time to savour success, they had thrown doubt on each finding, proving time and again, that there could be no mistake. And no one drew attention to the fact that they had worked day and night, forgetting all about time.

The objective data obtained by the Donets group were so irreproachable that D. I. Blokhintsev, Corresponding-Member of the USSR Academy of Sciences, then director of the Joint Institute, usually carping when discussing the results of experiments, declared:

'This is perhaps the first work in which it is impossible to point out a fault of any kind.'

The next week the news was published. 'Element 102 produced at Dubna', the Moscow papers said. And pictures of the three young fellows from Dubna appeared in papers and magazines.

They were pestered with questions:

'What is the new element like? What colour is it, white, dark, or silvery?' journalists asked them.

'It is like a feather of the Firebird', Donets joked. 'If a piece were ever obtained it would explode immediately with dazzling brilliance. Its period of decay is only eight seconds. In three winks half of it is gone.'

Flyorov 'escaped', as usual, to the Pamirs. Shche-

golev, abandoning all hope of beating the reporters off, put all his notes at their disposal. There was quite a commotion.

But that was only the beginning.

As Donets had said in his paper, the Dubna results were very different both from the theoretical calculations and from the results obtained at Berkeley in 1958.

Since the isotope 102^{254} obtained in Berkeley decayed for three seconds emitting alpha particles, and spontaneously disintegrated after six seconds, spontaneous fission of isotope 102^{256} should accordingly occur in approximately 0.02 second, and element 104 would only live five millionths of a second. That is to say, their synthesis would simply have to be abandoned as it bordered on the impossible.

But the unimpeachable experimental data of Shchegolev and Donets differed from the theoretical estimates by a factor of 400 for alpha decay, and of 100 000 for spontaneous fission.

Something was rotten in the state of Denmark!

Then Flyorov, having consulted his loyal cohort, posed a herculian labour. He suggested rechecking all the known facts about element 102 and to check them with new, improved techniques and precision instruments. Great strides had been made in experimental techniques in those years, and the Dubna workers had experience of accurate and rapid identification of elements by physical methods, and had verified data at their disposal on the laws governing production of transuranic elements in various nuclear reactions.To put it simply, Flyorov decided to employ all the most up-to-date knowledge and instruments to obtain every possible isotope of element 102 in carefully controlled experiments.

The time-honoured command went out: 'All hands on deck!' Almost all the laboratory's staff were invol-

ved in the work: Shchegolev, Donets, and Ermakov, of course, and others we also know—Druin, Skobelev, Fefilov, Mikheev, and Lobanov.

To begin with the properties of isotopes 102^{254} and 102^{256} were verified. The methods of identification were all those we know, i.e. by their 'daughters' and by the direct characteristics of the alpha particles. The results of the two experiments proved quite unexpected, though they were in full agreement.

Isotope 102^{256} behaved exactly as it had in earlier experiments; isotope 102^{254}, thought to have been produced at Berkeley, would not match up with its identifying marks. Its half-life proved to be about 60 seconds rather than three, as thought in 1959, and its alpha-decay energy 8.1 MeV instead of 8.3 MeV. Spontaneous fission occurred in less than 0.01 per cent of cases, rather than in 30 per cent.

In general, they experimented at Dubna for three and a half years to investigate the properties of six isotopes of element 102 with mass numbers of 251, 252, 253, 254, 255, and 256. The absolutely reliable information on their properties obtained often differed from that previously established by the American physicists.

At the same time Shchegolev, Donets, and Ermakov synthesized a new isotope of element 103, or lawrencium, employing the same technique as the Americans, and continued the investigation of its properties, which the people at Berkeley had not completed. By bombarding a target of americium-243 with accelerated oxygen-18 ions they produced the isotope lawrencium-256, with emission of five neutrons. Its half-life of the isotope was 45 seconds and its maximum formation cross-section 6×10^{-32} square centimetre. Carefully verified data gave its dominant mode of

radioactive decay as alpha decay, with electron capture in a very small fraction of cases.

In the autumn of 1966, to clear up the misunderstanding, Ghiorso and his group—Sikkeland, Matti G. Nurmia, and others—in the heavy ion laboratory of the Lawrence Radiation Laboratory of the University of California, in Berkeley, in turn checked the data on 102 isotopes in a series of very precise experiments differing somewhat from Dubna's. They bombarded curium targets with accelerated carbon ions in an improved HILAC with more intense ion beams, and produced and identified all of them with masses from 251 to 257 inclusive. According to Ghiorso their results agreed with those obtained at Dubna within the acceptable limits of statistical error. This double check also provided an interesting solution to the riddle of the 102^{254} isotope originally produced at Berkeley.

The first observations at Berkeley confirmed that its half-life was not three seconds as they had thought earlier, but approximately the 55 ± 5 seconds found by Donets and Shchegolev in 1965. But the 1959 experiment seemed quite accurate and no matter how Ghiorso and Flyorov racked their brains over the embarrassing discrepancy in the data, they could find no reason for it. Polikanov, Druin, and Oganesian visited America and discussed the situation there in Ghiorso's laboratory. They went over the whole experiment together, step by step, and still no one could find any appreciable error. But the discrepancy was there! Finally new experiments revealed that the activity obtained in 1959, both alpha decay and spontaneous fission, was due not to isotope 102^{254} at all but, probably, to quite another one, 102^{252}.

Such was the long drawn-out epic of element 102. There still remained the business of its name.

'A rose by any other name would smell as sweet, but would an element?' said a report 'Russians See Element 102' in the January 1967 issue of *Physics Today*.

'Number 102, officially known as nobelium and occasionally called rutherfordium, has been renamed joliot-curium...,' it continued.

In spite of the journal's apprehensions, naming of the element did not become a serious problem.

Ghiorso wrote to Flyorov on 20 March 1967 that in the end they had concluded that the simplest solution to the problem of naming the element would be to leave it in peace.

For the development of science it is not important where and by whom a discovery is made. The main thing is that it has been done. Science cannot help becoming more and more international. Its torch is handed on from generation to generation, and from country to country. To master the forces of nature, mankind unites its efforts.

Various groups of scientists have contributed greatly to the discovery of the transuranic elements. And though they are only human, and every one of them, no matter how selfless, would be delighted and happy to name a discovery after his native land or a great national hero whose work had been for the welfare of mankind, that cannot be a matter for disagreement and is always settled, somehow or other, to mutual satisfaction. We don't have to look for examples.

Element 104, though nameless for two years, did not suffer in the least and remained No. 104 just the same when it legitimately received its high-sounding name of 'kurchatovium' after the founder of Soviet atomic science and technology, Igor Kurchatov.

The 104th element of the Periodic System may prove the most interesting of all the transuranic ele-

ments, Glenn Seaborg, the famous discoverer of most of them, has said.

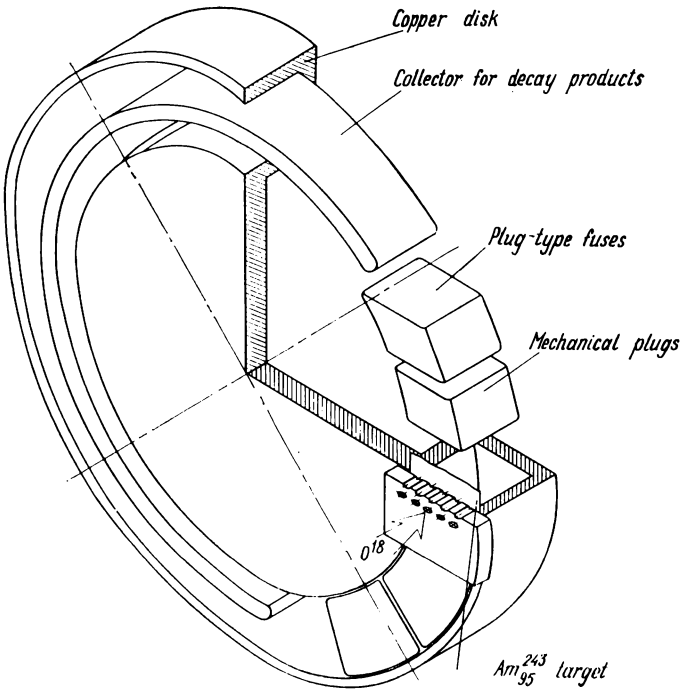
Let us remind you that, in his theory, element 104 should start an absolutely new family of the heaviest elements, for element 103, lawrencium, became the 'last' in the very heavy actinide series. So element 104 could hold many surprises for both physicists and chemists. It was not clear where its place in the Table was and what remarkable secrets it might disclose. For a hypothesis to become a theory it must be verified by experiment. Only element 104 itself could provide the evidence whether it really possessed the properties ascribed to it and so confirm the new view of Mendeleev's Periodic Law.

So it was only natural that the synthesis and proved separation of a sufficient quantity of element 104 roused special interest in Berkeley and Dubna.

But as we have already said, the further we go in Mendeleev's Table, the more unwillingly Nature retreats, and the more stubbornly and cunningly she clings to her secrets. At any rate, element 104 was hidden away very carefully.

Ideally, this element could apparently be produced by using a target made of the heaviest known element (lawrencium) and the lightest of charged ions (the hydrogen nucleus or proton) as projectiles. But even submicroscopic amounts of lawrencium were not available and its employment was still an unrealizable dream. So the American physicists bombarded californium with accelerated carbon ions. But the desired effect was not obtained. At Dubna they decided to bring up their 'heavy artillery' and proposed bombarding plutonium with multiply charged ions of heavy neon-22.

The idea was that the plutonium nucleus, having captured a neon ion, would become an excited com-



Schematic diagram of the Dubna apparatus for synthesizing isotopes of element 103

pound nucleus and be transmuted, after emitting four neutrons, into the heavy isotope 104^{260}. The reaction cross-section would be very small, and it was supposed that element 104 would only be produced once in 10 000 million events.

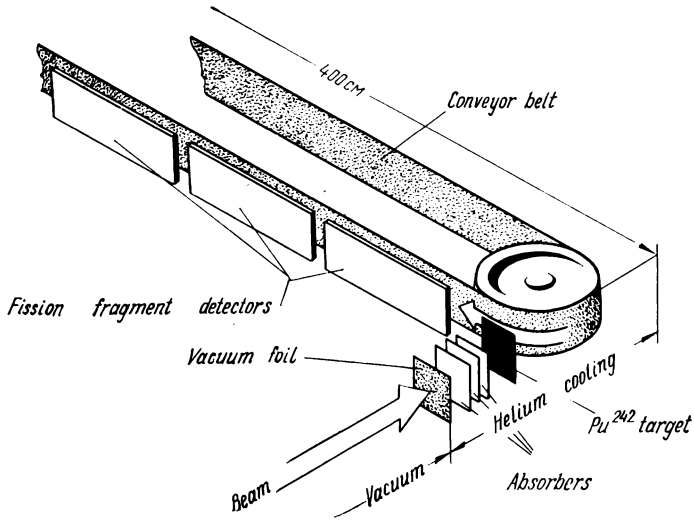
According to the experimental estimates, and contrary to the views of the theorists, its life was expected to be between one thousandth of a second and

one second. That is a very short period, virtually an instant, but quite detectable by modern instruments.

Armed with this scanty and not very encouraging information the young physicists, chemists, and technicians of the Laboratory of Nuclear Reactions (Oganesian, Lobanov, Kuznetsov, Druin, Perelygin, Krasnoslav Gavrilov, Svetlana Tretyakova, and Vasily Plotko), with Flyorov at their head, began to 'round up' the mysterious element.

Unfortunately, the double recoil technique that had proved so useful before could not be employed. The heavier the nucleus, the more readily it decays and breaks up into two fragments. Spontaneous fission is the principal mode of decay of nuclei beyond the limits of Mendeleev's Table and that deprives physicists of any chance of detecting them by their 'daughters'. Another method just as reliable had to be thought of.

The compound neon-plutonium nucleus ejected four neutrons to become a nucleus of 104^{260} only once in a thousand million events. And this precious, one in 10^9, nucleus immediately disintegrated, breaking up into fragments. Absolutely reliable detectors were called for, fragment detectors completely insensitive to other particles. Strange as it may seem, these wonder detectors proved to be most ordinary materials, mica and glass. As already mentioned, fission fragments make pock-marks in glass when they hit it that can easily be detected under a microscope after the glass has been etched with a weak solution of hydrofluoric acid. The main advantage of glass detectors is that no other particles (protons, neutrons, or alpha particles) will leave the slightest scratch on it. This feature, you may remember, was employed in studying the spontaneous fission of isomers. In fact all the



Schematic diagram of apparatus for synthesizing element 104

techniques used were much the same, except for improvements, as those employed earlier.

The nuclei produced in the reaction flew out of the target and landed on a moving nickel conveyor-belt that withdrew them from the 'hot zone' and carried them four metres past the glass recorders. While on the belt, the nuclei split leaving tracks on the glass. The half-life could easily be measured from the speed of the conveyor and the distribution of the tracks.

But because the formation of nuclei of element 104 was so very rare an event, it was of no little importance to eliminate any interference that might be caused by uranium fission fragments developing under the impact of neutrons when the ion beam of ions hit the tar-

get. Even one hundred millionth of one per cent of uranium could frustrate all their efforts. For that reason, plates of phosphate glass and lavsan, which have a much lower content of uranium, were used instead of ordinary glass.

The energies of the bombarding ions and the time intervals between them were chosen so that they would eliminate any background of other disintegrations, e.g. the spontaneously fissioning isomers now interfering and the nuclei of element-102 that would be produced in abundance.

Element 104, was produced atom by atom, one every five or six hours.

The researchers did not leave the cyclotron for days. For greater reliability, i.e. for surer control and to guarantee against breakdown, the experiments were performed with two probes. In addition, the speed of the belt and disks, and the spacing between the glasses were varied.

Each experiment lasted 50 to 60 hours continuously. When the repeated pressing of the counting button of the analyser made the hands numb, a treadle was rigged up so it could be pressed by foot.

The time spent on the machine was already counted in months. The team took turns to sleep, and saw dancing oscillograph serpents in their dreams. Flyorov conducted diplomatic negotiations to soothe their infuriated wives.

It is probably very difficult sometimes to be the wife of a physicist, and not only of a physicist, but of any one 'dedicated', who has an overwhelming passion for work. Oganesian, Shchegolev and Karnaukhov were excellent husbands and fathers. They dearly loved their wives, and their sons and daughters. But when an experiment was on! There was only one woman who could understand it, and then not without

difficulty. That was Oganesian's mother. She used to send 'refreshments' in to them at night, hot sausages, sandwiches, tea in a thermos.

They well remember the day when an emitter with a half-life of 0.3 second was registered. The result was so feeble, so barely distinguishable, so like a splash that they sneeringly called it the 'wart' on the decay curve. All the same they managed to study the wart's excitation function—the dependence of element yield upon the energy of the bombarding ions. And to everyone's delight it was what they had expected. Now it was a matter of statistics.

As soon as bombardment had finished, they all gathered without a word in the photographic laboratory where Svetlana Tretyakova and Perelygin were busily engaged with the glasses.

'Well, is there anything?'

'Nothing.'

Nothing. Nothing. Nothing. Here's a track. Again nothing.

'This is sadistics not statistics,' the lads said ironically.

The warning lamps lit up again: 'Keep Clear', 'Cyclotron Working'.

Belts and glasses were replaced again and again, and the battle for atoms went on. Somehow they had to make the apparatus a little more sensitive. Gavrilov was looking for the best possible way to make targets. Plotko, the mechanic, was performing miracles perfecting the probes, and was nick-named the Wizard.

At last an emitter with a lifetime of 0.3 second was registered quite distinctly, reliably, and stably. Everything indicated that it was a heavy isotope of element 104 with a mass of 260.

But as usual in the laboratory, they again began to try and disprove the obvious. To guarantee against

possible error, uranium-238 was bombarded with neon-22, and plutonium-242 with ions of oxygen-18 and neon-20. All these reactions were zero for element 104^{260}, i.e. could never produce it. And in fact, to their great joy no emitter with a life of 0.3 second was detected.

All the experimental data of sufficient reliability confirmed production of isotope 104^{260}. On the memorable day when the relentless and incorruptible Tretyakova confirmed production of 150 nuclei of the new element Flyorov was in Moscow. After phoning him, Druin rang me at Novosti out of friendship. I caught Flyorov literally on the hop and somehow got into his car. I'd never have forgiven myself if I'd missed that chance to be in at the birth of a new element.

By six p.m. we were in Dubna. Everybody was excited and happy—Druin, Oganesian, Polikanov, Lobanov, Plotko, even Lyuba, the secretary, and Annie, the typist, and no one thought of going home.

They plugged in the electric samovar that everyone in the laboratory is very fond of, and which is carefully hidden in the weirdest places from snooping firemen in rolles of drawings, behind the concrete blocks of the neutron shield, in the secretary's safe.

While the samovar was heating, I made the most of my scoop, asking numerous questions. Then I began writing the first article. We all edited it collectively. Around one o'clock in the morning reporters from TASS and Moscow Radio arrived with a tape-recorder, cameras, and flash equipment. We were drinking tea from the samovar in the chief engineer's office and eating sandwiches that Oganesian's thoughtful mother had sent in. Flyorov produced a bottle of Georgian wine from somewhere.

'A vintage one', he said, putting it on the table.

We drank the health of the new-born element and

V. A. Druin

its first 150 atoms, then the health of its parents. And then we toasted its future 'brothers' and all expected new elements up to number 150.

'Give me something for a keepsake, please,' I asked.

'Would you like a disk with daughter nuclei?' gallant Yuri Oganesian promptly asked in return.

'Or some glasses with the tracks of fragments?' suggested Lobanov.

We left the laboratory on a summer night that smelt of pines and the river, walking in a long line, hand in hand, and wanted very much to sing but we couldn't because the town was still asleep.

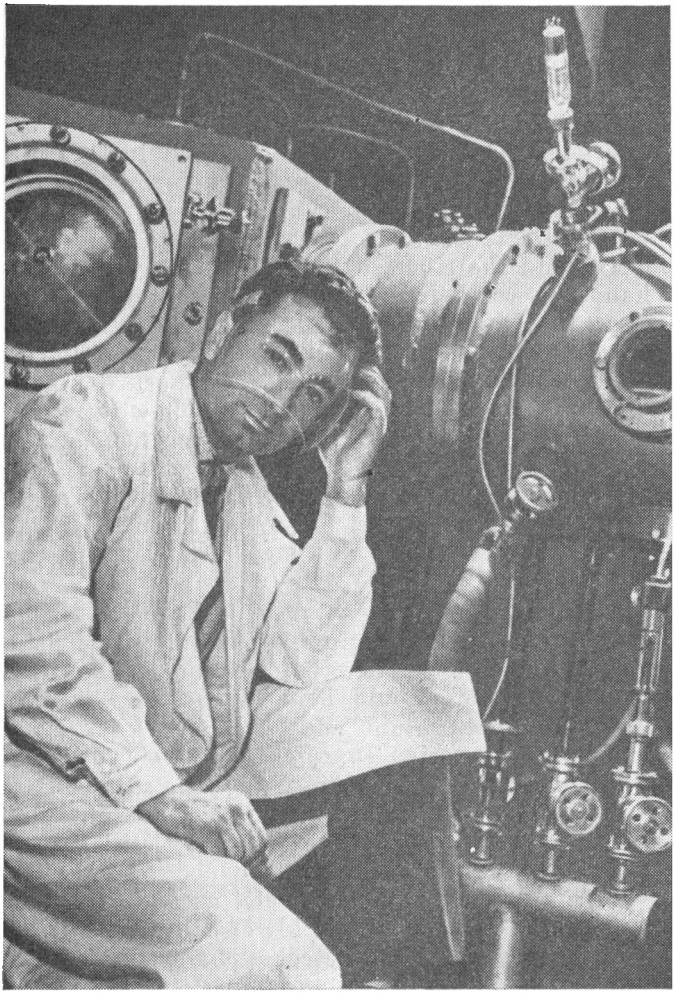
At six a.m. Druin came to the hotel to drive me back to Moscow. He had to make a report at nine at the Kurchatov Institute. I had the article with me and was impatient to inform the whole world of another victory over nature.

All the way to Moscow Victor talked to me of his visit to Ghiorso in America, and of the experiments they were preparing to continue study of the properties of element 104.

In Berkeley, as soon as they finished modifying HILAC, they would begin experiments to confirm our discovery. The methods used would be the same; only the reactions would be different: curium with oxygen and californium with carbon.

They were preparing equipment of two types. One would be used to measure the path of the recoil nuclei and their angular distribution in order to show that the characteristics of the spontaneously fissile emitter with a life of 0.3 second corresponded to what was expected from the compound nuclei needed to synthesize element 104. The second bit of equipment of improved sensitivity was to detect alpha-active isotopes of element 104.

The Dubna physicists were designing various logical



Yu. A. Oganesian

schemes for new experiments based on all the possible combinations of reactions between plutonium and neon.

Druin's team was preparing an experiment with a much improved technique to study the alpha decay of element 104. The idea behind it was that, with a change in the energy of neon, five neutrons could be ejected from the intermediate compound nucleus, instead of four as before in the same plutonium-neon reaction. A different isotope 104^{259} would be produced. Unlike the even-even 104^{260} it would have an even number of protons but an odd number of neutrons and so should prefer to emit alpha particles rather than splitting spontaneously into two fragments. The energy of the alpha particles could be expected to be 9.2 MeV and the half-life of the isotope 0.2 second. In this field of energies background interference is less and the nuclei knocked out of the target in the new experiment would, moreover, not fall onto a metal conveyor but into a helium jet, moving at the speed of sound into an insulated space evacuated to a high vacuum. A small brass collector, the shape of a Maltese cross about a centimetre across, would be positioned in the path of the jet. The helium would flow across it but nuclei would be left on its surface and collected on its arm. After bombardment the cross would be rotated mechanically through 90 degrees to position it in front of a semiconductor detector of high resolution while another arm would be ready for a new batch of atoms from the target. Thus nuclei from the target's surface would not stick anywhere and the emitted alpha particles would not lose their energy, as they would not wedge into belt or disk. That would permit much more precise and selective measurement of their energy, with an accuracy up to 10 keV, and the energy

of alpha particles, of course, is the main 'visiting card' for recognizing nuclei.

The mechanical device would be specially adjusted so, that immediately particles with an energy around 9.2 to 9.4 MeV emerged, the motor would be stopped for a certain time, depending on the half-life of isotope 102^{255}. The thing was that alpha decay of element 104, as with element 102, should yield a daughter product, this time an isotope of element 102 with a mass of 255. Its half-life and energy had already been accurately determined by double checks. That meant that the radioactive properties of the new isotope would be recorded in two ways: (a) directly from its 'visiting card' (alpha-particles) and (b) from its 'daughter', the remaining isotope 102^{255}.

Two years went by. I was again in Dubna at the Laboratory of Nuclear Reactions (again in connection with element 104). Now it was complete victory. The laboratory's chemists had found a way to determine its chemical properties.

The accelerator had been stopped in the morning 'for a break' of 90 minutes while something was readjusted; the heavy cast-iron door opened as if of its own accord, the automatic lock hospitably inviting one into the cavern of Sesame. Every time I enter this huge room with its high ceiling, and walk across the chequered tiles spelling out 'Danger Area', I always suddenly feel breathless with excitement. Say what you will, it is no joke to peep directly into the very bowels of the 'furnace' of modern sorcerers. On the left is a small desk, an ordinary office one, nothing special. There one must leave one's wrist watch. If you don't, and approach the machine with it on, it will stop for good and all. The magnetic field is too much for it. The cooling water gurgles peacefully, and the heated metal gives off a sweetish odour.

'Don't forget to stroke the lines of force,' laughed Anatole Pleve. It was not really a joke. Or rather, it was our private joke. The first time I entered the hall he had asked me whether I had ever felt magnetic lines. I took offence, of course. Did he take me for a silly chit? But without another word he had handed me a screwdriver; as soon as I took hold of it I felt that something pulling it away from me quite strongly. If I relaxed my arm a little it was pulled quite distinctly in a definite direction. Joking apart, I was literally stroking magnetic lines of forces.

Through a small aperture with transparent lead glass ionized gas gleamed all shades of pink heat; ionized gas is plasma, the same as the neon that glows in the tubes of electric signs, but quite different in temperature and energy. Close to the aperture is the place where the shining, corrugated copper 'head' of the probe is inserted, brought directly up to the accelerator on a light wheeled cart. But now the probe was off to one side and a technician was removing a cassette from it and giving it to the chemists (who were now the big noises in the Laboratory). In a small room separated from the cyclotron hall by a double concrete wall was the realm of Ivo Zvara and Yuri Chuburkov. Its walls were covered with transparent tubes, very picturesque with their crimson, bright-blue, and green liquids and gases. A small pump sighed at regular intervals. Zvara and Chuburkov spent day and night at the recorders. They can stay there without their wives, Tamara and Ida, being offended; for they continue the research in a lab on the floor above.

Before describing what these chemists thought up (their role in the discovery of element 104 was a major and responsible one, for this element was to become the start of a new family in Mendeleev's Table), let

us look briefly again at the problem of naming new elements.

Element 104's space remained without a name for two years, despite the fact that it had been discovered. Those two years were needed for repeated confirmation of its discovery so that no shadow of doubt remained, for the slightest doubt is all the stimulus a true scientist needs to continue the search, the launching pad for his flights of imagination. It took them two years to know exactly where, in what place in the Periodic Table, the new element (and its name) belonged.

Only then did the creators of element 104 have every right to name their brain-child.

During those two years, we must add, Flyorov, Druin, and Polikanov received many letters from young Pioneers, scientists wintering in the Arctic, seamen and engineers, doctors and journalists, suggesting names for the new element. There was 'moscovium' and 'sputnik', 'sovetium' and 'komsomolium', and 'druzhbium'*. It was a regular competition. The international team at the Laboratory decided the new element should be christened kurchatovium, which was approved by the administration and the Learned Council of the Joint Institute.

After reporting its synthesis and identification to the tenth anniversary session of Council Flyorov was instructed to write the new name on the big Periodic Table hanging in the conference hall, and he did so to tumultuous applause.

NEW FLASH CHEMISTRY

It is an empirical rule that the most interesting theses and papers are read at the most inappropriate times. June 1966 was no exception.

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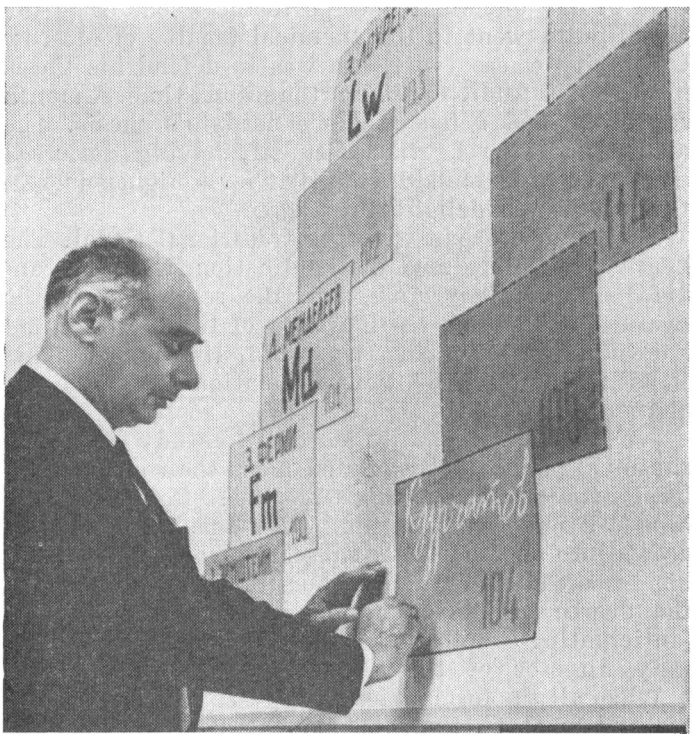
* From Russian *druzhba* friendship



G. N. Flyorov writing the name of the new element kurchatovium into the Periodic Table

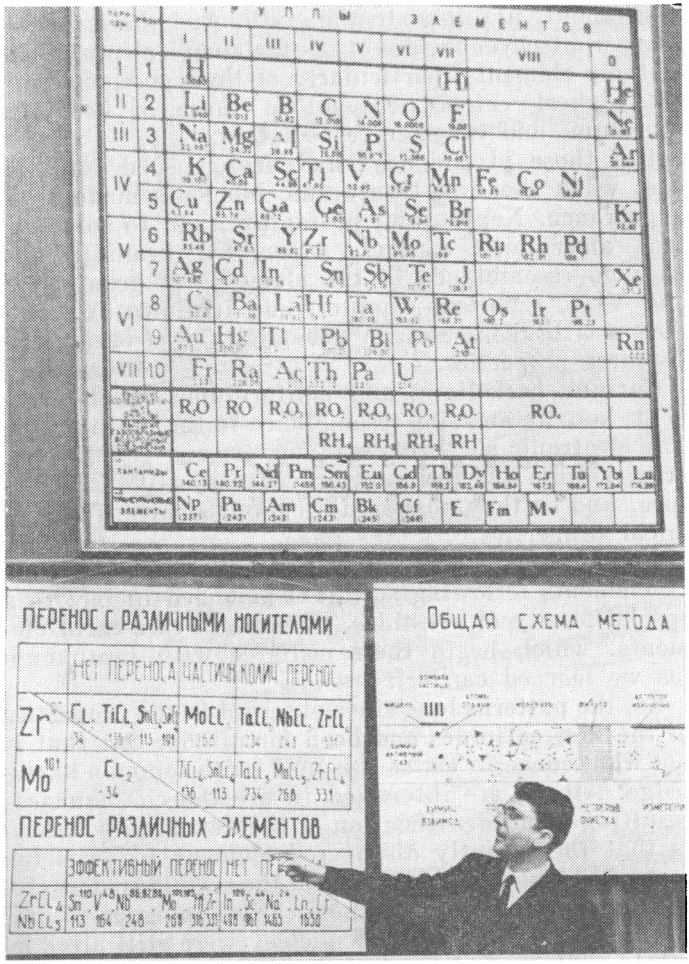
The working day was nearing its end. The weather was super-hot, without a breath of wind. It was the kind of day one wanted to go to the woods or to the river, but I went to the chemical faculty of Moscow University where Ivo Zvara was to defend his thesis in the North Auditorium. For the second time. A month earlier he had defended his candidate's thesis. The members of the Learned Council, having discussed it, suggested he should submit it for a higher degree, D.Sc. Ivo was delighted to agree.

The defence began with the traditional ritual. The Learned Secretary read the application, with the candidat's *curriculum vitae*, and the resolution of the Learned Council on resubmission of the thesis. I had known Zvara for a long time and, like many of his 'fans' in the hall, let the information go in one ear and out the other.

Ivo Zvara had come to Moscow to study from Czechoslovakia and had attended more than one lecture by eminent chemists in this same hall. After graduating he had started work with Flyorov and had gradually grown into an independent research worker, head of a big research team. In two hours or so he would have the degree of Doctor of Science conferred on him (anticipating events I will tell you that he is now deputy director of the Laboratory).

When all the formalities were over, Ivo took a pointer and went to the blackboard where his 'charts' were pinned. There were not many: a diagram of the apparatus, a few of the most interesting graphs and tables. The thesis was about the chemical properties of recently synthesized element 104.

In the idyllic days when uranium was the last element on Mendeleev's Table, no one doubted that thorium, say, belonged to the fourth group, protactinium to the fifth, and the heavy outsider we are tal-



Ivo Zvara defending his D. Sc. in chemistry at Moscow State University

king about, uranium, to the sixth. And there was no room whatsoever for doubt, as the chemical properties of these elements, particularly of their compounds of the highest valency, resembled those of hafnium, tantalum, and tungsten respectively.

But those idyllic days had been pushed into the past when the first transuranic elements made their appearance. Neptunium, plutonium, and to some extent americium, strongly resembled uranium and bore no resemblance to the elements of groups VII and VIII, rhenium, osmium, and iridium. The pattern was broken, and no periodicity was observable in their properties.

Curium, berkelium, and californium, which came next, bore an amazing resemblance to the lanthanides. The electronic shells of, say, curium and gadolinium, or berkelium and terbium, proved very alike in structure, and so they possessed a common pattern of chemical properties.

All this led to the quite justified conclusion that the 14 elements following actinium belonged in fact to a special family of actinides, like the 14 rare-earth elements, which begin their pedigree with lanthanum (as we learned earlier).

So, the patterns long since observed in the properties of the first actinides had been fortuitous. But that is not what concerns us, as it is now quite common knowledge. All we are interested in are the consequences resulting from identification of the new family, which is that the recently discovered element 103 was the last branch on the family tree of the actinides. The elements after it should be chemically analogous to hafnium, tantalum, etc. If Mendeleev were still alive he would call them 'ekahafnium' and 'ekatantalum'.

These elements should not only differ from the actinides but also differ from one another. The halcyon

days when chemical properties could easily be predicted had come to an end. No one knew what lay beyond No. 103. Hence the understandable interest with which chemists awaited information on the behaviour of No. 104.

The chemists would gladly have rallied round to synthesize new atoms not found on earth. But No. 101, mendelevium, was the last transuranic element whose chemical properties had been studied. Elements 102 and 103 had literally been produced in dozens of atoms that lived for only a few seconds. And that was not enough to determine chemical properties. They could only just manage the physical ones! That is how matters stood with elements 102 and 103, a situation that was just bearable. Theory could 'reconstruct' on paper chemical reactions that no one had detected; but when it came to element 104, it was another kettle of fish. New research techniques were needed that would enable the chemical properties of single atoms to be studied in ultrashort time. The job was definite enough but unbelievably difficult. 'Just to mix a solution in a glass with a little stick takes about a second', Ivo Zvara says. 'But the life of an isotope of element 104 is 0.3 second! And only one atom can be produced in five hour's continuous operation of the accelerator. We had to invent a kind of chemical dredge that would continuously separate the needed atoms from the barren rock.'

It took four years to develop the techniques and another two years for the experiments. Zvara and his colleagues, Chuburkov, R. Zaletka, T. S. Zvarova, M. R. Shalaevsky, B. V. Shilov, and others, worked on the assumption that element 104 was not an actinide. If that were correct, it should resemble hafnium in chemical properties and its higher chlorine compounds or chlorides would be very volatile, like

those of hafnium, whereas the higher chlorides of actinides were non-volatile and could easily be filtered out from element 104.

They performed dozens of experiments to find the best materials for transporting tubes, actinide filters, and detectors to record the precious nuclei of element 104. And dozens more experiments, each lasting two or three days, were needed to select the optimum temperature of the walls and gas, and the best compounds for the reaction with 'ekahafnium'. They proved to be chlorides of niobium and zirconium.

The principle of the experiment was quite simple. A neon ion hitting a plutonium-242 target would knock out an atom of the element sought, No. 104. The recoil nuclei would be slowed down in a stream of gas flowing behind the target. If free chlorine were present in the gas, the atoms would interact with it to produce 104 tetrachloride, $(104)Cl_4$.

Chlorides of analogous elements were added to the gas so that the precious molecules would not be lost in the immense (on an atomic scale) space.

Atoms of actinides formed as a side effect would be readily absorbed by the walls, while molecules of $(104)Cl_4$ and their analogues would be carried away in the hot flux and pass through special filters absorbing any chlorine compounds of actinides that had escaped capture in the walls. Then they would pass to the spontaneous nuclear fission counter. In disintegrating, the nucleus of element 104 signals that the atom has completed its 'gas run' from start (target) to finish (detector), and that means that it has behaved chemically in the same way as its analogue, hafnium.

The whole thing takes less than a third of a second!

The nuclear reaction products emerging from the thin target and colliding with vapours niobium and zirconium chlorides enter into exchange reactions with

them, and themselves become chlorides that are then carried by the stream of gas to the radiation detector. Elements of the third group are sorted out by the walls and deposited on the special filters. The technique enables chemical investigations to be performed directly in the cyclotron chamber. There was no other way, as nature gave investigators of element 104 too little time; so they were forced to develop this intricate method of analysis, which was not only continuous but also could begin a fraction of a second after the atom was produced.

In these crucial experiments element 104 imparted its properties precisely and unambiguously; it was not an actinide. It resembled hafnium, and so began a new series on the Periodic Table.

When Zvara finished reading his paper, almost no questions were asked. For one thing, the Learned Council was already well acquainted with his work from the previous defence, and for another—and this, of course, was the main reason—the information presented spoke for itself.

All three of the official opponents said as much. One of them, V. I. Goldansky, Corresponding Member of the USSR Academy of Sciences, with a reputation for wit, remarked:

'This is quite unusual work. Everything in it is unique, both the object studied and the techniques developed. Therefore, I shall indulge myself by putting aside my official testimonial and simply speaking about the problems facing radiochemistry. Since we have gone beyond the limits of the actinide series, every new element may display most unexpected properties. The technique presented for your judgement is the more interesting that it can also detect properties that we are not in any way expecting....'

After the formalities of the defence were at last

completed (the result, unlike those of the experiments performed, could be predicted quite accurately), Zvara was surrounded by friends, relatives, and colleagues.

It was all as it should be. The triumph, too. And it was quite in order that there are not, and cannot be, any limits to scientific search. From the scraps of conversation I heard I could guess that they were already talking about what element 114, and possibly 126, would be like.

HOW MANY NEW ELEMENTS CAN THERE BE?

Element 104—kurchatovium—is known. Element 105 was produced not so long ago at Dubna and it was suggested that it be called after that great physicist Niels Bohr. The time when synthesis of new superheavy isotopes can be planned like the production of conventional products, it would seem, is not very distant. And then what?

At any rate, experiments to synthesize elements 114 and 126 are being prepared both at Dubna and at Berkeley. Ideas on this are evolving quite rapidly and radically as our knowledge of the nucleus deepens and techniques are improved. But is it necessary to go so far? Will the cost and effort be justified?

It is not, of course, a matter of 'scalp hunting'. Or just of possible industrial applications. Then why are they trying to synthesize as many different isotopes as possible? The possible permutations and combinations of protons and neutrons are practically infinite. The actual number of protons, however, and the number of neutrons they can bind, is quite definite and is probably strictly fixed, and all the proton-neutron combinations cannot by any means, be realized. It is very, very important to know which combina-

tions have been realized in nature, and which not, as that will let us discover the laws governing the structure of the nucleus and construct a more accurate model of it.

But, as we know, the heavier a nucleus is, the more particles it contains, and the shorter is its life, and hence the more difficult it is to produce. A nucleus crammed with particles tends to break up spontaneously. The more protons there are in it, the greater are the Coulomb forces of repulsion and the greater the probability that the nuclear restraining forces will be unable to counter them.

So an increase in charge increases the probability of spontaneous fission. Does that mean that very heavy nuclei are virtually inaccessible? Or might there not be tiny islands of relative stability in the sea of unstable heavy elements? Or is it impossible to develop the superfast recording units to 'catch' such short-lived nuclei? What forecasts can be made about it? What do the theorists think? And what are the experimenters' ideas?

Let us hear what physicists have to say about further advance beyond the Table.

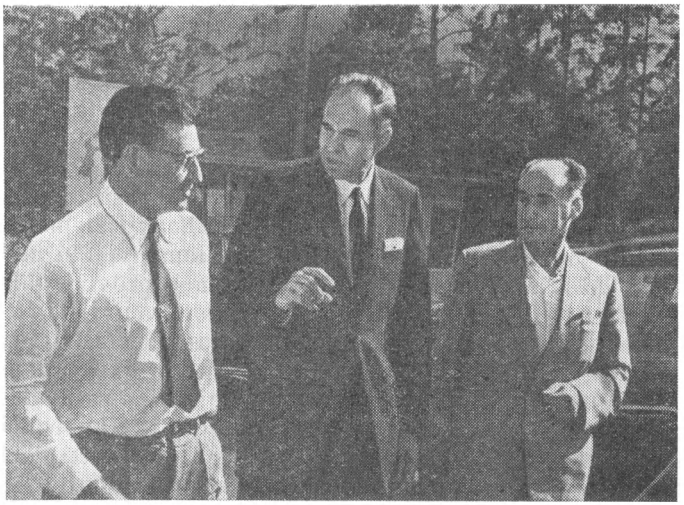
In April 1969 the *Scientific American* published an article 'The Synthetic Elements' by Seaborg and Justin Bloom, in which they wrote that 'theoretical calculations suggest the existence of closed nucleon shells at $Z=114$ and $N=184$ that exhibit great resistance to decay by spontaneous fission.

'Enhancing the prospects for the actual synthesis and identification of superheavy nuclei is the fact that the doubly magic nucleus $^{298}114$ is at the centre of a rather large island of stability in a sea of spontaneous fission. Stability against decay by spontaneous fission is highest at the centre, and instability increases as the edges of the region are reached.

'Indications are that the superheavy elements can be created only by bombarding target nuclei with sufficiently energetic projectiles consisting of heavy ions. Many experimental difficulties will have to be overcome. The yield of the desired product nuclei is predicted to be very small because the overwhelming proportion of the nuclear reactions lead to fission rather than to synthesis through amalgamation of the projectile and the target nucleus. The currently available target nuclei and projectiles lead to neutron-deficient nuclei that lie outside the island of stability. Projectile ions that will soon be available with the required energy should lead to nuclei that are just barely within the island and therefore will have half-lives so short as to make them difficult to detect. To reach the centre of the island may require the construction of new accelerators or modification of existing ones in order to furnish the heavy and energetic ions needed.'

These suppositions had been developed and concretized in 1967 by Flyorov, who put forward a number of daring ideas.

'I am sure', he said, 'that we will find a way out of the region of instability where we are now stuck. Analysing the possibilities we have concluded that if spontaneous fission is the main factor preventing synthesis of new isotopes and elements, we will have to use the old trick of experimenters. We will have to make this interfering factor work for us. We shall have to try and synthesize new elements by means of nuclear fission. How? By raising the charge of the bombarding nucleus higher and higher. Then the fission fragments of the resulting nuclei will gradually have higher charges. In the long run, in the extreme case, say, when uranium is bombarded with uranium we shall be able to produce almost all the isotopes of the most remote and heavy elements.



Alberto Ghiorso, Glenn Seaborg, George Flyorov (left to right) at Dubna

'In our laboratory at Dubna Oganesian and his chemists are already working on broad systematic research into the fission products of heavy nuclei induced by multiply charged ions. The experiments have shown that this method of producing isotopes is more effective than the normal ones using hot neutrons even when splitting uranium by neon.'

Encouraging estimates came from the theorists in 1968. Speaking that summer at the international conference on nuclear structure in Dubna, Flyorov dwelt specially on them.

'It used to be thought until recently that the limit of the periodic system was determined by competition of the forces of surface tension and the Coulomb forces of repulsion. But when we consider the stability of

the heaviest nuclei, we must take into account the non-uniformity of the distribution of energy over the nucleons, the "shell effect" in the liquid drop model. The calculations made by our Soviet theorists Strutinsky, Muzychka, and Nemirovsky, and also those of the joint group of American, Swedish, and West German workers, have indicated that the disastrously rapid fall in the decay curve of the heavy elements should "break" somewhere between elements 114 and 126. These nuclei and adjacent ones may prove stable and live thousand of times longer than would be expected if they obeyed the general rules. The accuracy of these results, of course, is far from what experimenters would like, because even a minor error in the calculations can give a big deviation from the expected lifetime; but of the fact that a region of stability of the heaviest nuclei exists there is now no doubt.

'From the work of the American physicist W.J. Swiatecki it is clear that the life of the most stable isotope of element 114, as regards spontaneous fission is years (an analogous result is given by estimates of its full life, including beta and alpha decay and electron capture). Similar calculations have also been made for elements of $Z=122-126$, but their lives, as regards beta and alpha decay, are not expected to exceed 10^{-3} second. So the question arises, how are we to get to the island of stability? We may land there by jumping over the region of unstable elements (100-110); but that can only be done by reactions with heavy ions.

'Since 1967 a group of American physicists—Swiatecki, Thompson, and others—have been trying to synthesize element 114. The heaviest particle that can be accelerated in HILAC at present is argon-40, so they have used the following reaction:

$$\text{argon}\,{}^{40}_{18} + \text{curium}\,{}^{248}_{96} = 114^{288} \rightarrow 114^{284} + 4n$$

The 114^{284} isotope is very far from the double magic nucleus 114^{288}, so hopes of getting 114 from this reaction were not great. In fact, the effect was not observed. A more optimistic reaction would seem to be:

$$\text{calcium}\,{}^{48}_{20} + \text{plutonium}\,{}^{244}_{94} = 114^{292} \rightarrow 114^{288} + 4n$$

'Calcium-48 has now been accelerated in our laboratory and background experiments carried out. But synthesis of element 114 will be made much easier as soon as it is possible to accelerate ions heavier than krypton. Thus, fission of uranium by xenon ${}^{132}_{54}$ would most likely yield the isotope 114^{305}, and the excitation energy of the fragment would correspond to the emission of four to six neutrons. As we proceed to the heavier elements (Z=120—126), it will be easier to choose the necessary combination of target and ion to synthesize isotopes with a mass number of 284.

'I would also like to remark that when we have heavier ions the fission fragments will fill up the greater part of the Periodic System, so there will be a chance of detecting new isotopes of any element, stable or unstable.

'Now I should like to touch on the very promising results reported by Prof. C. F. Powell on behalf of a group of British physicists. This team studied the elements in cosmic rays, employing photographic emulsion. Some years ago they detected high-energy traces of uranium in cosmic rays. More recently Powell's group sent photographic emulsions up in space probes and detected tracks in them made by particles whose ionizing capacity suggested that there might be elements among them with a charge equal to or greater than 110. If these results are confirmed in the near future, it will be possible to prove that superheavy elements can exist and can be synthesized.

'Given the particle velocity of cosmic rays, their densities, fission cross-sections, and other factors, we can roughly estimate the probable life of the superheavy elements detected in them. These estimates give an upper limit of the order of several million years. Moreover, if we can detect superheavy elements in cosmic rays with long lives there must be a group of isotopes with shorter lives that can be synthesized and studied on heavy-ion accelerators.

'The main task now, and a very difficult one, is to find a method of accelerating uranium ions and of demonstrating experimentally where and what types of reactions are feasible.

'The old cyclotron at Dubna enabled us to pass from helium to calcium, that is to increase the charge of accelerated nuclei by a factor of ten. Now the job is to create a machine that will let us go on from calcium to uranium, i.e. from number 20 to number 92.

'Personally it seems to me that this is the direction in nuclear physics and chemistry which will give the very best opportunities for synthesizing superheavy elements.'

Alberto Ghiorso considers that the two most important obstacles preventing production of elements heavier than 104 are their formation cross-sections and their half-lives, and that the heaviest target practicable today is a long-lived isomer of einsteinium-254.

In order to produce element 105, Ghiorso thought that at least six protons would need to be captured through bombardment, i.e. a carbon ion. The cross-section of the reactions would probably be less than one microbarn. To produce elements 106 and 107, the target would have to be struck by ions of nitrogen and oxygen, but their cross-sections are smaller by one or two orders of magnitude. The half-lives periods of the isotopes that could be produced in these reactions

would become progressively shorter and shorter and the difficulties involved increasingly greater. But the idea that these estimates could be mistaken prompts one, Ghiorso said, to think it is worthwhile trying. The view, held for some time, that the heaviest elements may prove to have a relatively stable region has not yet been refuted by anyone, and so Ghiorso thinks fusion of uranium with uranium is very promising. That could yield transuranic elements, both light and heavy, proton radioactive and neutron radioactive, and the excitation of the nuclei might prove to be not very high.

Recent theoretical work, like that of Strutinsky and Muzychka, mentioned by Flyorov, has depicted most alluring prospects for the synthesis of heavy elements. Having analysed in more detail the effect on nuclear stability of a filling of the proton and neutron shells close to 'magic numbers' (114 protons and 184 neutrons) they came to an interesting conclusion. Their calculations suggested that such a filling, contrary to the predictions based upon the liquid drop model, should lead to an extremely big increase in stability of the nucleus as regards spontaneous fission.

'There is real hope of being able to produce comparatively long-lived isotopes of elements with atomic numbers close to 114 and masses of 298,' says Strutinsky. 'And Muzychka's calculations have made it possible even to say where the region of stability will be found among the heaviest isotopes of these nuclei.'

Roughly speaking, the stability of element 114 will diminish a million times every two mass units. Therefore its isotopes with 296 and 298 nucleons should be the most stable. That is something concrete.

But what will be the chemical properties of the most distant elements of the periodic system?

An interesting hypothesis has been suggested by Goldansky.

'In advancing beyond element 118 we shall apparently be marching into the eighth period of the Mendeleev system. Various scientists have suggested that the arrangement of this period will be built the same as the sixth and seventh, i.e. it will contain 32 elements, element 126 being the chemical analogue of plutonium. It seems to me, however, that the situation will be much more interesting. Advance into the region of elements yet unknown and the laws governing the filling of electronic shells, formulated by Vsevolod Klechkovsky, lead to the conclusion that the eighth period of Mendeleev's system will contain 50 elements (that does not mean, of course, that we'll be able to produce all 50 of them), and that, instead of a 14-element group with properties similar to those of the rare-earth elements and actinides, this period will incorporate a group of 18 elements not encountered in the periodic system, from No. 121 to No. 138.

'The structure of the three outer electron shells, the sixth, seventh, and eighth, in the atoms of these 18 elements—let us call them octadecanides—will be quite similar and they will differ only in the structure of the fourth shell from the outside or fifth from the nucleus (i.e. in the number of the "*g*-electrons"). Therefore all the octadecanides will differ in chemical properties even less than the rare-earth elements do. The nearest analogue of all these 18 elements among known elements will be actinium.

'The possibility of such a structure in the eighth period will necessarily have to be taken into account in future radiochemical separation and investigation of elements in the vicinity of atomic number 126,

otherwise we may repeat the situation that experimenters found themselves in before Seaborg's actinide theory, when attempts to isolate and chemically identify elements with Nos. 95 and 96 from their oxidation to the hexavalent state failed.

'From that it is clear that synthesis of the elements of the eighth period and study of their physico-chemical properties will be of great interest not only for nuclear physicists but also for everyone concerned with general and inorganic chemistry.'

Despite gloomy hypotheses that very heavy nuclei, particularly those of elements with atomic numbers higher than 137, will collapse owing to their exceedingly high positive charge, Wheeler has shown that the electrons of atoms with atomic numbers even much higher than 137 will behave 'normally' because of the unlimited extent of the nucleus. For, from the angle of accepted views of the structure of electron shells, there are no limits to the existence of superheavy elements. The only limitations come from the instability of the nuclei themselves.

To sum up: theory authorizes the existence of elements up to No. 137. From a systematization of nuclear properties it can be supposed that the expected life of new transuranic elements with atomic numbers from 105 to 108 will be in the range of a few microseconds to several seconds.

The isotopes of transuranic elements with nuclei containing 160 to 184 neutrons are expected to be more stable as regards spontaneous fission.

Present-day data give grounds for thinking that nuclei with 114 protons and 184 neutrons, and 126 protons and 184 neutrons, will be especially stable, that is isotopes of the element 114^{298} and of element 126^{310}.

That is how the theoretical forecasts and hopes look.

But what are the possibilities of experiment?

'For us the report of theorists on the existence of "islands of stability" was like the cry of "Land ho!" to Christopher Columbus's sailors,' Flyorov recalls. The 'hunt for supernuclei' began first in his laboratory in two directions; the first, as before, on an accelerator for multicharged ions, to which a U-200 accelerator has been cunningly joined. The tandem machine enabled heavy elements (calcium and xenon) to be accelerated without any extra special outlay, and not only allowed work to begin on the synthesis of element 106 as soon as 105 had been obtained but also permitted them to move on to the 'islands of stability', elements 122 to 126. The reactions of nuclei with heavy ions are much more varied and yield a much wider spectrum of products, and still give experimental and theoretical physicists much trouble, since they have to build new models of nuclear interactions much more complicated than the merging of drops.

Another difficulty is that there is no firm ground, and that it is necessary to feel one's way. All that is known is the region where there may be something; but the extrapolation of properties by analogy with Mendeleev's Table is so tenuous that it is impossible to rely on it. All of which, naturally, does not make the job any easier, though physicists are full of optimism.

It would help them greatly if they could obtain positive results in the second direction of the 'hunt', namely in looking for supernuclei in nature. That search also began five years ago (around 1968) with what seemed a trifle.

If element 114 is an analogue of lead, one might try looking for it in very old stained-glass windows, in the glass in contact with the leads, or in crystal glass containing lead. The Czechoslovak and Polish

workers in the Laboratory brought bits of fourteenth century glass from old churches in their countries; and the Russian Museum in Leningrad provided fragments from wineglasses of the time of Ivan the Terrible.

Hundreds of samples passed through the hands of the Dubna radiochemists, Svetlana Tretyakova and Vladimir Perelygin. In some they detected strange traces resembling the disintegration tracks of a superheavy element. Then an old friend of the Dubna team, Dr. Peter Fowler, arrived from England. Calculations based on the known age of the Solar system and the life of uranium and plutonium indicated that the synthetic element plutonium must have existed in the Earth's crust in a concentration of 10^{-25} gram per gram. That is an infinitesimally small quantity when one considers that the concentration of uranium is 2×10^{-6} gram per gram. But there it is! Some theoretical propositions indicated that nuclei of superheavy elements might be formed in the flare-up of supernovas or in neutron stars and reach the Earth in cosmic rays. From Fowler's experiments it followed that one atom of a superheavy element might strike every thousand square metres of the Earth's surface in an hour (or ten atoms per square metre per annum). Not very dense, it must be admitted, but surely places could be found where particles from cosmic rays might be accumulated for thousands of years, isolated from terrestrial substances.

In 1970 physicists from Dubna went, with the backing of the Institute of Oceanology (USSR Academy of Sciences), to the central area of the Pacific Ocean on the research vessel *Vityaz*. From great depths of between five and eight thousand metres they brought up nine tons of odd rocks (dull, black, perfect spheres) of uncontaminated iron and manganese, known as

iron-manganese concretions, of ancient volcanic or cosmic deposition. To process them Vladimir Voropaev's group and workers from the All-Union Nonferrous Metallurgy Research Institute developed a new technology for the recovery of highly volatile elements (as it is supposed the superheavies would be). This technology, incidentally, like others developed by physicists, is very useful in industry.

In 1971 three expeditions went into the attack: one on Kamchatka for volcanic ash; another (jointly with the Institute of Geology and Mineralogy) headed by Chuburkov, one of the Laboratory's leading chemists, for underground water and hot springs on the Cheleken Peninsula in Turkmenia. In the broiling sun of the desert a quartet of trailbreakers passed two million litres of underground water through an ion-exchange column, filtering 500 tons of salts from it, and separating from the salts metals that were analogues of superheavy elements (lead, thallium, etc.). Then they took the saturated resins from the column back to their laboratory for investigation by nuclear methods.

The third expedition went beyond the Arctic Circle to the Franz Josef Land archipelago. There, on Hayes Island, is a peculiar lake, known as Cosmic Lake, a relic of the Ice Age, whose geological age has been estimated at between 7000 and 10 000 years. Its surface is constantly covered with a layer of ice two metres thick, which does not allow plankton to develop. On the bottom is a layer of silt half a metre thick that might just preserve superheavy elements, or traces of their decay. On 26 August 1971 another quartet from Dubna, led by Vladimir Pokrovsky, set out on the M/s *Lena* for Hayes Island. They had been given only eight days by the Murmansk Shipping Line, the time needed to discharge and load the ship,

and in that time they had to extract at least a ton of silt. The lads worked with a will, and by the date of departure had loaded onto the ship eleven tons of silt, packed in wooden boxes. The vessel was not delayed for a minute, although there was a very tense moment during the loading of the last two boxes, when their tracked cross-country vehicle went through the ice and had to be pulled out by a tractor. But all was well, and the ancient silt reached Dubna safely.

Concretions, silt, volcanoes, underground waters—all are 'earthly' objects. But there is also 'primitive matter' available, the protoplanetary matter from which the stars and worlds of the Universe are formed, though considerably altered. In its pure form it can only be found in outer space, but occasionally it falls on the Earth in the form of meteorites.

Meteorites most likely preserve superheavy elements or traces of their fission or disintegration. There is a hypothesis that xenon is a decay product of the superheavy elements they are hunting so assiduously at Dubna. Meteorites are far from identical in their nuclear composition. Those in which there is an abnormal amount of xenon are called carbonaceous chondrites. They have another, most important feature; they have almost no uranium. And uranium is the chief obstacle to the search as it is the only known terrestrial element that, like the superheavies, divides spontaneously. Traces of its decay can be taken for traces of a superheavy element, which makes things terribly difficult with supersensitive apparatus. So the less uranium there is, the more sensitive the analysis. Another advantage of meteorites is that exactly how much of the superelements would be found in them can be calculated as a ratio of uranium, since the rate of half-decay (the half-life) of each element in it, and the age and size of the meteorite itself, are

precisely known. For greatly altered terrestrial substances the calculations are much more difficult to make.

But carbonaceous chondrites fall when and where they list, without regard for the desires of physicists. The individual examples found are preserved in museums and are of immense scientific and monetary value, national treasures. The Dubna scientists developed fine techniques for studying them without breaking them up or altering their composition. That in itself is a great achievement of nuclear science, for it is impossible to bombard a specimen even with neutrons without irreversibly altering it. Consequently, neither neutron activation analysis nor proportional counters, in which the material studied is ground to a powder, were suitable.

A supersensitive apparatus with a background noise equal to one pulse a year was used by Andrew Popeko and Nicholas Skobolev. It cannot be used in any premises on the surface of the Earth, for it is 'swamped' by cosmic rays. So it had to be installed 500 metres down in a dry salt mine in Transcarpathia, which was exactly right for studying earthly samples of silt, metals, and ash.

The meteorites so needed, the Efremovna and Saratov, were furnished under a gentlemen's agreement (which was scrupulously observed) by the USSR Academy of Sciences and sent to the mining village of Solotvino in Transcarpathia. Then Ivo Zvara, now Corresponding Member of the Czechoslovak Academy of Sciences, brought a valuable gift from America (where he had been conducting a joint experiment with American physicists) from the U.S. National Museum in Washington—a sample of the Alendo meteorite that fell in northern Mexico. The first results were hopeful.

At the time of the Communist *Subbotnik** in the USSR, on 21 April 1973, several workers from the Laboratory of Nuclear Reactions in Dubna, Eichler from the German Democratic Republic and Plotko, Perelygin, and Chuburkov of the USSR, developed a new technique for chemical extraction of the glass-like substance, olivine, from meteorites. One gram of olivine, after wandering in space for tens of millions of years, accumulates as many tracks of heavy and superheavy elements as two tons of plastic or photographic emulsion would if orbited for a whole year. No one, however favourably disposed to the people at Dubna, could put two tons into orbit for them for a year. So five kilograms of the Maryalahti meteorite which is especially rich in olivine, was donated to them for joint research with the Mongolian State University and Helsinki University in Finland.

Search in nature, trials with synthetic elements created in the laboratory, all mean using more powerful and more precise equipment. A new accelerator for multicharged ions is being built at Dubna that will accelerate such heavy elements as lead and uranium. The Superhilac is coming into use (at the time of writing) in the USA, and two even more powerful ones are being built in the Federal German Republic.

This heightened interest in heavy ions is not simply excited by the importance, romance, and excitement of the search for new elements. The nuclear physics of the next decade will basically be the physics of heavy ions—such is the view of a frequent visitor to Dubna, the famous Danish physicist Aage Bohr. The

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* *Subbotnik*, a Soviet custom of working voluntarily on a Saturday without pay. The proceeds of the country-wide subbotnik of April 21 are devoted to scientific and social projects of national importance, like cancer research.—*Editor.*

Soviet physicists Flyorov, Vladlen Barashenkov, and Muzychka agree with him. Another, perhaps no less important aspect of heavy ions has been discovered quite recently that may not only hold the future for nuclear physics but become the basis of an entirely new branch of engineering.

'A beam of heavy ions is now in about the same position as a laser beam ten or fifteen years ago,' Barashenkov (deputy director of the Dubna Laboratory of Nuclear Reactions) affirms.

A laser beam acts on matter at a single point, heating it strongly; a beam of heavy ions can be directly wedged into the inner nuclear structure of matter and alter its chemical composition according to a preordained programme. The remarkable property of heavy ions, the possibility of 'driving' a big chunk of nuclear matter into another one, that is to say of acting on any property of any material, opens up unlimited prospects for engineering. It is a special feature of the process that it goes on at comparatively low temperatures and permits almost full automation and 100 per cent reproduction of the properties of the new materials.

By bombarding silicon or germanium detectors, which are widely used for rapid activation analysis by prospecting geologists and environmental physiologists (to check the environment), with ions of boron, phosphorus, or tantalum, the quality of the semiconductors can be improved. By regulating the depth of the material bombarded, the size of which depends on the type of ion used and its energy, and the means used to etch it. Thus these nuclear filters (or screens or 'nucleopores' as they are also called) have openings of ideally exact shape, of a number and size easily controlled. Molecular-virus filters can now be obtained varying in diameter from 40 Ångström units to a few

microns. Since bacteria are little more than a fifth of a micron in diameter, nuclear filters enable beer, wine, and liquid foods of every kind to be sterilized cold. In microbiology nuclear screens are used to separate various types of cells, (in particular to sort out cancerous blood cells), to obtain drinking water cleansed of bacteria, to purify air, dyes, etc. The cost of a nuclear filter is not very high. The preliminary estimates made at Dubna are that they will cost around one rouble a square metre (those now obtained in nuclear reactors, which are much inferior in quality, cost ten roubles a square decimetre, or one thousand times as much).

Study of new atoms is very important for understanding the world around us. And difficult as each new step in this field is the expenditure in it will be recouped a hundred times over.

In the long run there is only one truth, that great physicist Albert Einstein used to say. One should be venturesome and faithfully devoted to science to sacrifice the whole of his life and all his strength no matter how slim his chance to succeed may be.

A little serendipity would not be amiss, we would add. But where there is boldness and devotion to science, serendipity is never slow to come. If now you also believe that, I can count my job well done.

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The synthesis of elements heavier than uranium has opened up new spheres in our knowledge of nature and new fields of nuclear physics and chemistry. The transuranic elements, the heaviest in Mendeleev's Periodic Table, are throwing new light on the structure of the atomic nucleus and the mechanisms of reactions between nuclei, enabling us to understand the chemical properties of newly produced elements, and to clarify ideas on the Periodic Law.

The story of current nuclear physics is full of surprises and is an intriguing tale of imaginative exploration and painstaking, persistent search, of heartbreaking failure and unexpected results. The author, Elaine Knorre, a science correspondent of the Novosti News Agency, knows many of the people involved personally, and has herself been present at some of the crucial moments in the discovery of new elements. Thus she has an inside knowledge [illegible] that gives her account a [illegible] will find attractive and re[illegible]

Other popularl[illegible] nuclear physics are *The* [illegible] *Power of the Atoms*, both